



Natural convective flow between  
by R Baughman

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of  
MASTER OF SCIENCE in Mechanical Engineering  
Montana State University  
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Abstract:

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The description of a new inner body heating tape design is contained in this thesis. In addition, the use of spray paint tracer particles in silicone oil has also been presented since this has previously not been reported in any of the available literature.

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Date December 28, 1972

NATURAL CONVECTIVE FLOW BETWEEN A BODY AND ITS SPHERICAL ENCLOSURE

by

RICHARD CARL BAUGHMAN

A thesis submitted to the Graduate Faculty in partial  
fulfillment of the requirements for the degree

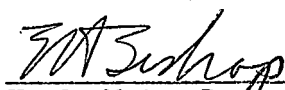
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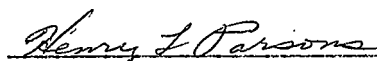
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## ABSTRACT

Natural convection flow visualization studies between a cooled outer sphere and enclosed heated inner-body configurations are reported. The inner bodies were 1) vertically eccentric spheres and 2) hemispherically-ended vertical cylinders, both utilizing air, water, and a silicone oil as the test fluids. The effect of downward eccentricity was observed to encourage the formation of large diameter vortex cells in the chimney region. Positive (upward) eccentricities, which yielded smaller gap widths in the upper portion of the flow field, led toward three-dimensional unsteady tendencies. Most of the fluids and configurations tested were found to maintain a peripheral flow pattern at small temperature differences, where the high velocity fluid layers primarily followed the contours of the inner and outer geometries. For larger temperature differences, however, unsteady vortex structures in the upper region often resulted. The cylinders did show a significant linear length effect which might have been expected in regard to flow-separation. The silicone oil, which was very viscous relative to the air and water, appeared to act as an unsteady flow damper. As a consequence of this, unsteadiness did not significantly affect the surrounding stagnant fluid. Tables of the experimental results are included and should provide ease of flow categorization within the ranges of independent variables given.

The description of a new inner body heating tape design is contained in this thesis. In addition, the use of spray paint tracer particles in silicone oil has also been presented since this has previously not been reported in any of the available literature.

## NOMENCLATURE

| Symbol     | Description                                                                    |
|------------|--------------------------------------------------------------------------------|
| $a, b$     | Characteristic lengths                                                         |
| $c_p$      | Specific heat                                                                  |
| $g$        | Acceleration of gravity                                                        |
| $Gr_L$     | Grashof number, $g\beta\rho^2 L^3 \Delta T/\mu^2$                              |
| $k$        | Thermal conductivity                                                           |
| $L$        | Gap width, $r_o - r_i$                                                         |
| $Pr$       | Prandtl number, $\mu c_p/k$                                                    |
| $r_{avg}$  | Average radius $(r_o + r_i)/2$                                                 |
| $r_i$      | Inner body radius                                                              |
| $r_o$      | Outer sphere radius                                                            |
| $r_\theta$ | Distance from geometric center to a selected location on surface of inner body |
| $\bar{R}$  | Dimensionless radius ratio $(r - r_\theta)/(r_o - r_\theta)$                   |
| $Ra_L$     | Rayleigh number, $Gr_L \cdot Pr$                                               |
| $\bar{T}$  | Dimensionless temperature $(T - T_o)/(T_i - T_o)$                              |
| $T_{am}$   | Arithmetic mean temperature (page 20)                                          |
| $T_i$      | Inner body temperature                                                         |
| $T_o$      | Outer sphere temperature                                                       |
| $T_{vm}$   | Volumetric mean temperature (page 20)                                          |

x

| Symbol     | Description                                            |
|------------|--------------------------------------------------------|
| $\beta$    | Coefficient of thermal expansion                       |
| $\delta$   | Displacement from concentric position                  |
| $\epsilon$ | Eccentricity, $\epsilon = \delta / (r_o - r_i)$        |
| $\theta$   | Angular position measured from upward<br>Vertical axis |
| $\rho$     | Density                                                |
| $\Delta T$ | Temperature difference ( $T_i - T_o$ )                 |
| $\mu$      | Dynamic viscosity                                      |

## CHAPTER I

### INTRODUCTION

Until recently, the bulk of natural convection heat transfer investigations have been primarily concerned with infinite fluid environments as the receiving medium. Unfortunately, the results of these studies cannot be extended to include natural convection processes which occur within finite enclosures. Since the increasingly important disciplines associated with nuclear design applications and electronic instrument packaging require knowledge regarding the heat transfer and fluid mechanics problem between an inner body and its enclosure, research efforts have been concentrated in this direction.

Analytically, the general enclosure problem solution cannot be determined because the governing differential equations are non-linear and coupled. Additional complexities arise because (1) the normal infinite atmosphere boundary layer assumptions are no longer valid, (2) the pressure distributions are unknown, and (3) when flow unsteadiness develops, the boundary conditions become unknown. As a consequence of this lack of available information, and the fact that general analytical solutions are nonexistent for enclosed configurations, experimental investigations become necessary in order that the resulting fluid flow and heat transfer phenomena can be adequately described.

In 1964, heat transfer studies for natural convection between isothermal concentric spheres were initiated by Bishop, Kolflat, Mack, and Scanlan [1,2,3] utilizing air as the gap working fluid. This work included both heat transfer and flow visualization results. More recently, however, Scanlan, Bishop, and Powe [4], and Weber, Powe, Bishop, and Scanlan [5] have extended the earlier works by varying the inner body geometries in addition to using water and silicone oils as test fluids. Yin [6] conducted further fluid-flow behavior investigations with concentric spheres at significantly higher Grashof numbers and observed different characteristic patterns with water as the gap fluid.

Further review of the literature has revealed that an extensive amount of heat transfer results have been obtained relative to the fluid-flow phenomena reported. Without an understanding of the convective flow processes which develop within the enclosure gap, a serious lack of pertinent information exists since plausible explanations of the heat transfer results and temperature profiles are not always in order.

The work presented within this thesis is therefore an extension of previous studies aimed at further supplementing the unknown details associated with the convective flow fundamentals. Specifically, flow visualization investigations of eccentric spheres with air and silicone oil and concentric, hemispherically-ended cylinders utiliz-

ing water and silicone oil as gap working media are reported. Criteria for predicting the fluid-flow behavior have been described for the temperature differences and geometries studied. Photographs accompanied by sketches of the resulting flow patterns aid in the explanation of past investigators' hypotheses regarding the temperature profiles which they reported.

Another important aspect of this thesis presentation involves the design and application of an entirely different inner body heating system than that used in the past. In order that the potentially hazardous pressurized Freon-11 heating method could be eliminated, a heating tape design arrangement was developed.

## CHAPTER II

### LITERATURE REVIEW

Free or natural convection heat transfer is directly related to the flow and temperature characteristics of the physical environment under consideration. Past investigators have attempted to adequately describe these processes, but, since the analytical problem is generally quite formidable, only the elementary geometries have been studied. Publications for these cases are numerous. As additional complexities arise, which is typical of free convection within confined spaces, less information is available in the literature. The resulting consequence is that a series of experimental investigations have been reported.

Using dimensional analysis, Jacob [7] has derived the pertinent dimensionless quantities which appropriately conform with basic natural convection phenomena. The following is a list of those parameters:

$$Gr_a = \frac{\rho^2 g \beta \Delta T a^3}{\mu^2}, \quad (2.1)$$

$$Pr = \frac{C_p \mu}{k}, \quad (2.2)$$

and 
$$L = \frac{a}{b}. \quad (2.3)$$

In the above equations,  $Gr_a$  and  $Pr$  are the Grashof and Prandtl numbers respectively. The length parameter ( $L$ ) is characterized by the dimensions "a" and "b" of the geometry under investigation. An additional

convenient term called the Rayleigh number is also found in the literature,

$$RA_a = PR \cdot GR_a \quad (2.4)$$

An excellent review of the simple geometries is given by Yin [6]. The remaining portion of this review has been restricted to those configurations which are more closely associated with this investigation.

#### SPHERICAL ANNULI

The natural convection process occurring within the annulus between concentric spheres was first considered by Bishop, et al [1,2,3]. Both the heat transfer and the flow visualization results were reported using air as the gap fluid. The basic flow patterns observed were (1) the crescent eddy, (2) the kidney-shaped eddy, and (3) the "falling-vortices" type flows. Diameter ratios of 1.19, 1.72, and 3.14 with temperature differences ranging from 5°F to 60°F were studied. Presented by Bishop [8] is a detailed discussion of these patterns. Correlations are also given for each flow in regard to the resulting temperature distributions.

More recent attention by Weber [9] has extended the earlier works to include greater impressed temperature differences and the utilization of water and silicone oils as gap working media. The bulk of this work, however, pertained strictly to the heat transfer results. In

order to allieviate some of the uncertainties generated by this work, Yin [6] and Yin, Powe, Scanlan, and Bishop [10] documented the flow behavior results by increasing the Grashof number range. With air, their findings at least qualitatively agreed with Bishop's [8] for small temperature differences. For large temperature differences, however, a three dimensional spiral flow was observed for some cases. The resulting water flow patterns were (1) the steady and unsteady "dog-face" [6], (2) the tertiary, and (3) the three-dimensional spiral. A complete discussion of the range and existence of each flow pattern has been indicated in these works.

#### ECCENTRIC SPHERES

Natural convection to a cooled sphere from an enclosed, vertically eccentric, heated sphere was described by Weber [9] and Weber, Powe, Bishop, and Scanlan [5]. Heat transfer and temperature profile data were obtained for both positive (upward) and negative eccentricity geometries with water and silicone oils as the test fluids. Of primary importance, it was determined that a negative eccentricity enhanced convective activity whereas a positive eccentricity had just the opposite effect and favored conduction. These authors hypothesized the nature of the flow fields under various conditions, but expressed a need for further study of the detailed effects which occur for wide variations in the independent variables.

## CONCENTRIC CYLINDERS

The appearance of concentric, hemispherically ended, vertical cylinders in the literature was first presented by Weber [9] and later by McCoy [11]. The effects of aspect ratio (the total height of the cylinder divided by its diameter) and Prandtl number were investigated. It was established that the cylinders yielded results which varied significantly from the sphere data. Since it was postulated that multicellular type flows existed for some of the cylinder cases, future flow studies were demanded.

## CHAPTER III

### EXPERIMENTAL APPARATUS AND PROCEDURE

#### EXPERIMENTAL APPARATUS

The apparatus used in this investigation was partially redesigned to duplicate the results obtained by Yin [6] and to further study the characteristics of natural convective flows using different inner-body configurations than those previously reported. Figure 3.1 shows the assembled apparatus utilized for this thesis work. The cubical enclosure seen near the center of the photograph contains the isothermal outer sphere to be more thoroughly described later. The peripheral equipment includes (1) the light source on the right, (2) AC Variac power supplies and temperature monitoring instruments below, and (3) the cooling system on the left.

The primary purpose of the approximately 16.0 inch cubical enclosure was to permit a closed system to be employed. The coolant entered at the top face and was directly incident on the vertical axis of the outer sphere since this region was generally the hottest. The coolant then exited through ports located on the bottom face. Other necessary features of the enclosure were that (1) it served to support the outer sphere and its inner body, and (2) it had three sides fabricated from plexiglass to allow the resulting flow patterns to be illuminated, visualized, and photographed.

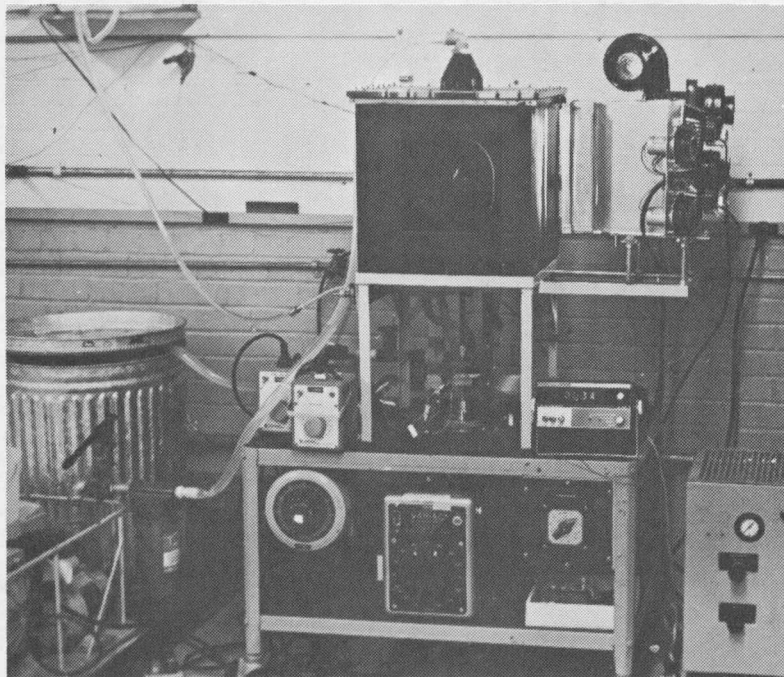


Figure 3.1 Apparatus Assembly

The outer sphere consisted of two glass hemispheres with an approximate inside diameter and thickness of 9.77 and 0.21 inches, respectively. As can be observed in Figure 3.2, a cylindrical base was cemented to one of the hemispheres for mounting purposes inside the cube. The position of this base relative to the hemisphere was chosen such that the parting plane would not obstruct the frontal viewing angle of the flow pattern. A tapered collar insert was machined to fit inside this base. This tapered element had a 0.525 inch hole bored through it and functioned to align and partially support the stem of the inner geometry.

Since water and silicone working fluids were injected through ports in the base, it was necessary to vent the top so that trapped air could escape. The 0.20 inch hole which permitted this is shown in Figure 3.2.

Once the inner body was placed inside the hemisphere with the support base, the hemispheres were joined together using a silicone sealant which (1) prevented any leakage between the coolant and gap fluid, and (2) permitted ease of disassembly.

The same diameter inner spheres, 7.00, 5.50, and 4.50 inches, investigated by Yin [6] were used for the eccentric study. In addition, hemispherically-ended vertical cylinders were also investigated. The dimensions of these were 4.50x6.50, 4.50x8.50, and 7.00x9.00 inches (diameter x overall length).

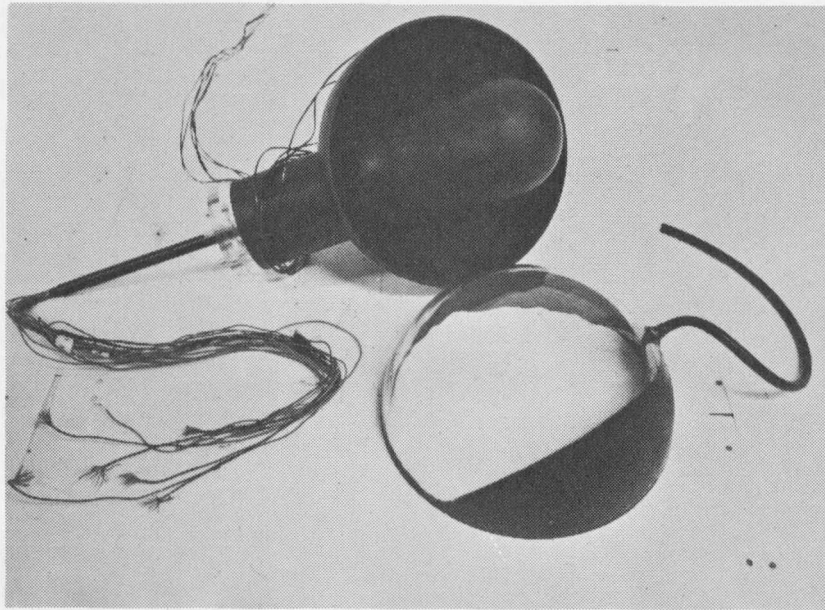


Figure 3.2 Glass Hemispheres with Mounting Base

The previously pressurized Freon-11 systems developed for these bodies were eventually replaced by a heating tape arrangement. Adhesive-backed metallic tapes, 0.020 inch thick and 0.125 inch in width, were spirally affixed to the inner surface of the 0.030 inch thick copper wall bodies. Illustrated in Figure 3.3 is the 7.00 inch inner sphere. Each separate hemisphere had four sections of tape to which individual power leads were then connected. To insure that the tapes remained fastened, a thin layer of silicone sealant was applied over the entire inner surface. After all necessary wires were attached inside the body and it had been soldered together, a 0.25 inch hole was drilled through the top of the body. Through this hole, powder-like glass eccospheres were funneled to fill the inner body thereby minimizing internal convection heat transfer. This fill port was then soldered shut. By varying the voltage input to each tape, the outer surface can be isothermally maintained. The high thermal conductivity of the copper wall allowed sufficient heat transfer in the lateral direction to aid in making the surface isothermal.

The positioning of the inner body within the outer sphere was controlled by a 0.50 inch diameter stainless steel tube soldered to the bottom of the inner body along its vertical axis. This stem exited through the previously mentioned tapered collar and was sealed by two O-rings. To minimize lateral heat conduction along the stem, plastic shrink tube insulation was used. In addition to positioning,

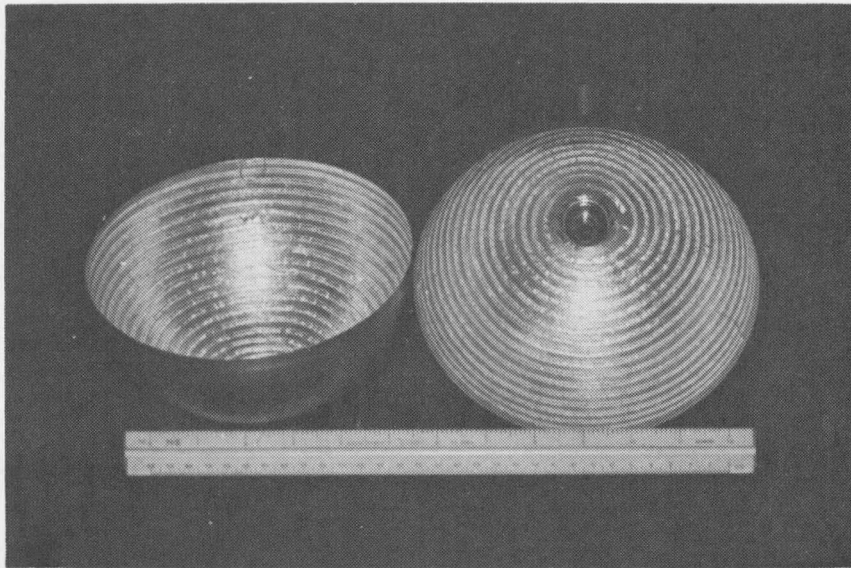


Figure 3.3 Disassembled Inner Sphere with Heating Tapes

the stem served as an outlet for the power leads and thermocouple wires.

Copper-constantan thermocouples were employed for monitoring the inner and outer body temperatures. On the outer sphere, 0.025 inch holes were drilled at various locations through the glass wall, and the thermocouples were epoxied at the bottom of the hole flush to the inside surface. For the inner bodies, the holes were drilled through the copper wall and the thermocouples were soldered flush to the outer surface. All of these wires were then connected to a selector switch box from which a DC millivoltmeter indicated output voltages.

Two types of cooling fluid systems were utilized. With air in the gap, forced air served as the cooling medium. With liquids as the working fluid, chilled and filtered water coolant was supplied. These compatible index of refraction combinations minimized optical distortion through the viewing angle.

The lighting was supplied by two 650 watt home movie camera lamps in a light-tight enclosure. A 0.25 inch slit provided a nearly collimated light beam which entered the cubical enclosure on an adjacent side from the frontal viewing direction.

In order that the flow pattern could be observed, tracer particles were needed. With air as the working fluid, cigar smoke gently introduced into the gap yielded best results. Impurity particles found in "Ajax" detergent made excellent tracers with water since these particles

are highly reflective and neutrally bouyant. This mixture was made by adding 10 drops of detergent per gallon of boiled distilled water cooled to 100°F. For the 350 cs silicone oil, fluorescent orange spray paint particles acted as tracers. The silicone oil is a Dow Corning 200 fluid with 350 cs representing the kinematic viscosity at 25°C. Spraying this paint over an open container of silicone and allowing the atomized particles to fall on the surface with later mixing produced good results.

Photographs were obtained using a 4"x5" Calumet Camera with Kodak Tri-X Pan Professional film. In order to reduce optical reflections created by the cubical enclosure, the glass outer sphere, and the inner body, all surfaces were painted flat black except in those regions where illumination and visualization of the flow pattern were necessary. The clarity of the photographs was greatly enhanced as a result of this measure.

#### EXPERIMENTAL PROCEDURE

The desired inner body was selected and painted flat black before inserting it within the separated glass hemispheres. A 24 hour curing time silicone sealant was then applied to the parting line. Installation of the above into the cubical enclosure was then followed by connection of all thermocouple and power leads along with the plumbing of the cooling system.

The positioning of the inner geometry occurred next. For the eccentric study, eccentricities of  $\pm 0.750$  and  $\pm 0.375$  were considered. The eccentricity  $\epsilon$  is defined as

$$\epsilon = \frac{\delta}{r_o - r_i}, \quad (3.1)$$

where  $\delta$ ,  $r_o$ , and  $r_i$  are the deflection from the concentric position, the outer sphere radius, and the inner sphere radius, respectively. The cylinder investigations were of a concentric nature only.

To locate the concentric position, the inner body was raised and lowered within the limits of the glass sphere and a pointer fastened to the bottom of the stem indicated the travel on a scale. The mid-way location was then established.

The operating procedures were as follows:

- (1) Except for air, which was initially present, the working fluid was introduced into the gap and allowed to fill by gravity feed from containers of the prepared mixture.
- (2) The outer sphere cooling and the inner body heating systems were turned on. The AC Variacs which controlled individual heating tapes were separately adjusted until the isothermal condition for the desired temperature difference across the gap was achieved.
- (3) Sufficient time was permitted so that the entire configuration would arrive at thermal equilibrium.

- (4) The flow pattern was observed and photographed. With air, cigar smoke had to be gently injected into the gap. After sufficient time, a fully developed flow pattern, which could then be studied, would appear. After prolonged periods of time, however, the smoke became too dispersed and had to be replenished. The gap was therefore purged by pumping in clean air. This procedure of introducing smoke for the next run was then repeated.

The following pertinent information was recorded on data sheets:

- (1) Run number,
- (2) Gap fluid,
- (3) Atmospheric pressure (for air only),
- (4) Eccentricity,
- (5) Inner body temperatures,
- (6) Outer sphere temperatures,
- (7) Heater tape input voltages,
- (8) Comments and written descriptions of the flow pattern.

A computer program was written for the XDS Sigma 7 digital computer to reduce the data to a desired form. Included in the Appendix is the program used for the eccentric sphere configurations.

All of the configurations tested for this thesis presentation are listed in Table 3.1.

TABLE 3.1

## INNER GEOMETRIES AND TEST FLUIDS INVESTIGATED

## ECCENTRIC SPHERES

| Dimensions<br>(inches) | Air | Water | Silicone 350 |
|------------------------|-----|-------|--------------|
| 4.50                   | X   |       | X            |
| 5.50                   | X   |       | X            |
| 7.00                   | X   |       | X            |

## CONCENTRIC CYLINDERS

| Dimensions<br>(inches) | Air | Water | Silicone 350 |
|------------------------|-----|-------|--------------|
| 4.50 x 6.50            |     | X     | X            |
| 4.50 x 8.50            |     | X     | X            |
| 7.00 x 9.00            |     | X     | X            |

## CHAPTER IV

### EXPERIMENTAL RESULTS AND DISCUSSION

This chapter has been organized in the following manner. Sections describing the flow patterns corresponding to the eccentric spheres and the concentric cylinders are included. Subsections based on the gap working fluids are also found. Finally, a discussion of the experimental results is given.

Before proceeding with the flow descriptions a few remarks are in order regarding the Grashof number. For all of the flows observed, a minimum Grashof number corresponding to a temperature difference of approximately 5-10°F was investigated. This limiting value was chosen in order to reduce any error caused by a slight variation over either the outer sphere or the inner body. The maximum Grashof number values reported were limited by 1) the voltage input to the heating tapes (140 volts/tape length), 2) an inability to maintain the outer glass sphere at an isothermal temperature, or 3) the disappearance of the detergent particles in the water studies at temperatures greater than about 130°F, whichever condition occurred first. Also indicated in each section are the reference temperatures upon which the fluid properties were determined and the geometric length parameters incorporated into the Grashof numbers.

## ECCENTRIC SPHERE FLOW PATTERN DESCRIPTIONS

The geometric length parameter ( $L$ ) contained in the Grashof number was selected as the difference between the radii of the outer and inner bodies ( $r_o - r_i$ ). For the evaluation of the fluid properties, two characteristic temperatures were considered. One method provided values based on the volume weighted mean temperature ( $T_{vm}$ ) defined as follows:

$$T_{vm} = \frac{(r_{avg}^3 - r_i^3)T_i + (r_o^3 - r_{avg}^3)T_o}{r_o^3 - r_i^3} \quad (4.1)$$

The other reference temperature employed was an arithmetic mean defined as:

$$T_{am} = \frac{T_i + T_o}{2} \quad (4.2)$$

Unless otherwise stated, the Grashof numbers presented are calculated using equation 4.1.

GAP WORKING FLUID: AIR

The first inner body investigated for the eccentric study was the 4.50 inch sphere positioned at eccentricities of  $\pm 0.375$  and  $\pm 0.750$ . Considered first was the largest positive eccentricity case ( $+0.750$ ). For a minimum Grashof number of 92,000 ( $\Delta T = 7^\circ F$ ) to a value of 160,000 ( $\Delta T = 12^\circ F$ ), a steady, "necked-down" crescent-eddy pattern, similar to

that shown in Figure 4.1, was observed, with the exception of the vortices in the upper region. These vortices appeared for Grashof numbers larger than 160,000. The necked upper region of the main cell was a result of the physical geometry of the system. The overall pattern (excluding the extreme upper region of Figure 4.1) consisted of several distinct regions. Two of these are the thin high speed layers of fluid which moved upward and downward along the inner and outer spheres respectively. The cooler fluid which moved downward exited into a relatively stagnant region at the bottom of the main cell. Surrounded by the high velocity fluid was the most noticeable transition region which focused on the centrally located eye of the main cell where negligible motion occurred.

When temperature differences greater than  $40^{\circ}\text{F}$  were imposed, an unsteady flow resulted and was characterized by the formation and shedding of vortices between the upper portion of the inner sphere and the enclosing outer sphere (Figure 4.1). The rate at which these vortices were created appeared to be proportional to the impressed temperature difference. The vortices were initially formed by a counter-rotating cell which developed near the separation point of the upward flow of the primary crescent-eddy cell along the inner body. In order to satisfy continuity, slugs of fluid were randomly injected from the vortex region into the main cell, disturbing it momentarily. This motion was observed up to a maximum Grashof number of 907,000 ( $\Delta T = 95^{\circ}\text{F}$ )

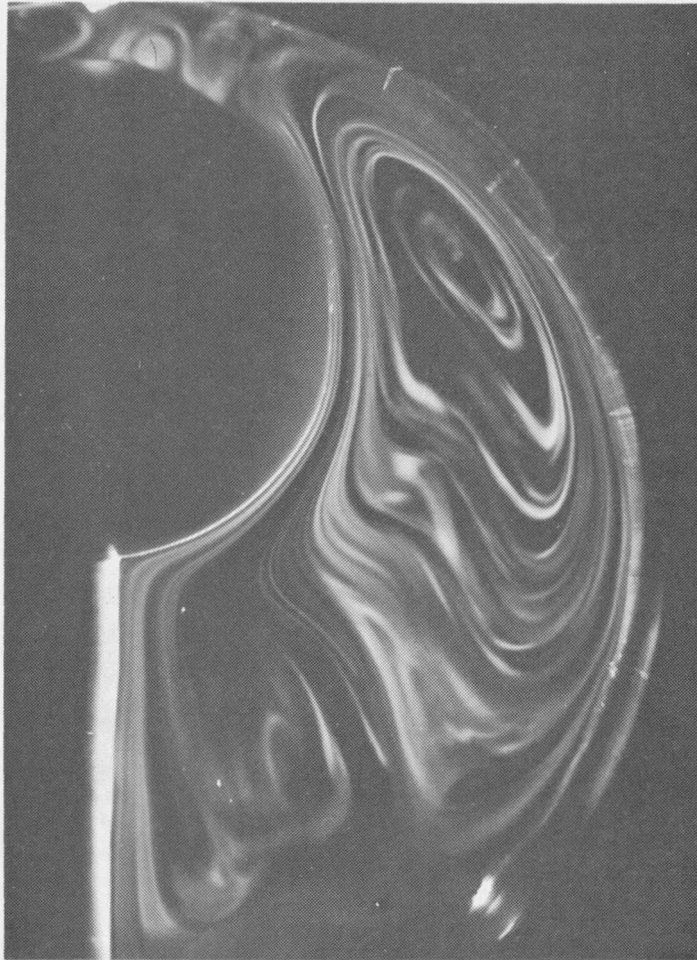


Figure 4.1 Photograph of +0.750 Eccentricity Air Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 200,000$$

$$\Delta T = 15^\circ F$$

with some three-dimensional flow characteristics being associated with the vortex region.

The next lower position of the inner body decreased the eccentricity to a value of +0.375. For this particular configuration, the results published by Yin, et al [10] for concentric spheres with a diameter ratio of 2.17 follow almost identically. Steady flow patterns existed for all observed Grashof numbers ranging from 110,000 to 970,000 ( $9^{\circ}\text{F} < \Delta T < 98^{\circ}\text{F}$ ). After having passed through the crescent-eddy type pattern for relatively low Grashof numbers, the kidney-shaped-eddy first described by Bishop [8] was observed (Figure 4.2).

The flow patterns corresponding to an eccentricity of -0.375 at the minimum Grashof number of approximately 100,000 ( $\Delta T = 8^{\circ}\text{F}$ ) remained representative of the crescent-eddy with its lower portion compressed as a result of the geometry. The appearance of additional interior cells was seen as the Grashof number was increased to about 190,000 ( $\Delta T = 15^{\circ}\text{F}$ ). This pattern, Figure 4.3, with its new cell centers, was still found to be steady. A further increase in the Grashof number ( $\text{Gr}_L > 420,000$ ) led to a distortion of the previous pattern, thereby yielding a very pronounced kidney-shaped type flow. This occurred up to the maximum observed value of  $\text{Gr}_L = 850,000$ . Unsteadiness prevailed within the interior of the kidney for Grashof numbers greater than 700,000 ( $\Delta T = 77^{\circ}\text{F}$ ). This unsteadiness was characterized by a somewhat periodic expansion and contraction motion, but this phenomenon did not



Figure 4.2 Photograph of the +0.375  
Eccentricity Air Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 870,000$$

$$\Delta T = 85^\circ F$$

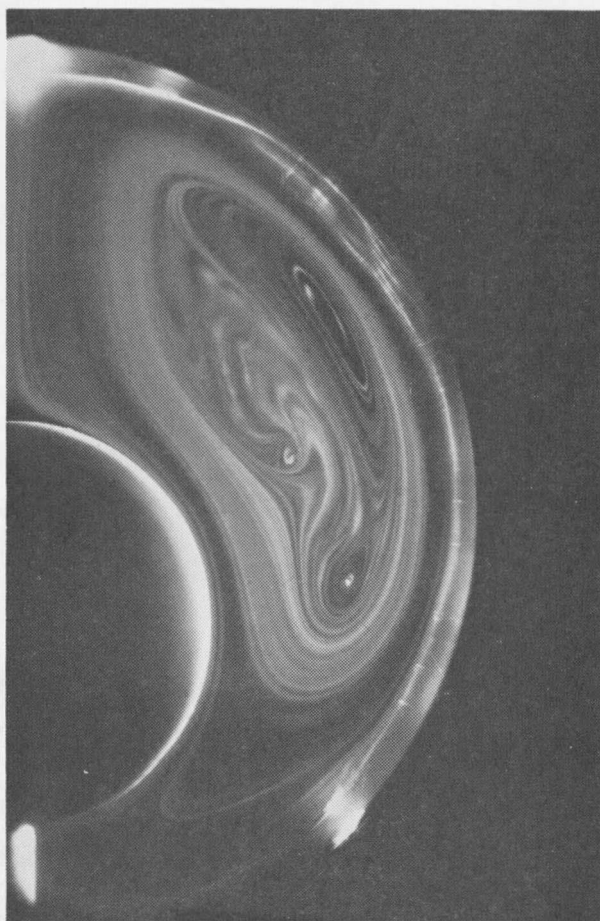


Figure 4.3 Photograph of -0.375 Eccentricity Air Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 400,000 \quad \Delta T = 31^\circ F$$

disturb the periphery of the overall flow field.

The lowest eccentricity of  $-0.750$  yielded a flow pattern illustrated by Figure 4.4. At the smallest Grashof number observed ( $Gr_L = 94,000$ ,  $\Delta T = 7^\circ F$ ), steady flow conditions prevailed. This steadiness persisted almost throughout the entire Grashof number range studied ( $Gr_{L,max} = 850,000$ ,  $\Delta T = 75^\circ F$ ). The high end of this range, however, indicated that interior unsteady motion was beginning to occur. The form of this unsteadiness appeared to be nearly identical to that described for the previous eccentricity case ( $-0.375$ ).

The other inner body considered for this eccentric study utilizing air as the test fluid was a 7.00 inch diameter sphere positioned at the same eccentricities as the previously described 4.50 inch sphere. The remaining descriptions of air flow patterns within this section are supported by sketches due to the fact that the outer glass sphere used earlier was replaced by an optically very poor one. This was necessary since the original sphere had become broken during experimental testing.

At the largest eccentricity investigated,  $+0.750$ , the minimum observed Grashof number of approximately 14,000 ( $\Delta T = 7^\circ F$ ) yielded a steady crescent-eddy type flow pattern. As the impressed temperature difference was increased to about  $15^\circ F$ , very slow, tangentially moving, counter-rotating vortex cells were observed within the extremely narrow gap near the top of the inner sphere (Figure 4.5). These vortices were found to be constantly disappearing and reforming in a somewhat random

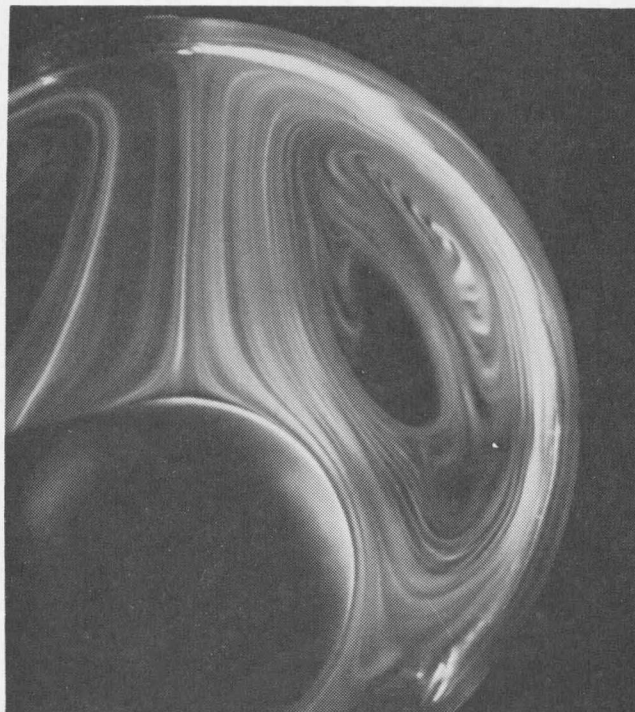


Figure 4.4 Photograph of -0.750 Eccentricity Air Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 700,000$$

$$\Delta T = 70^\circ F$$

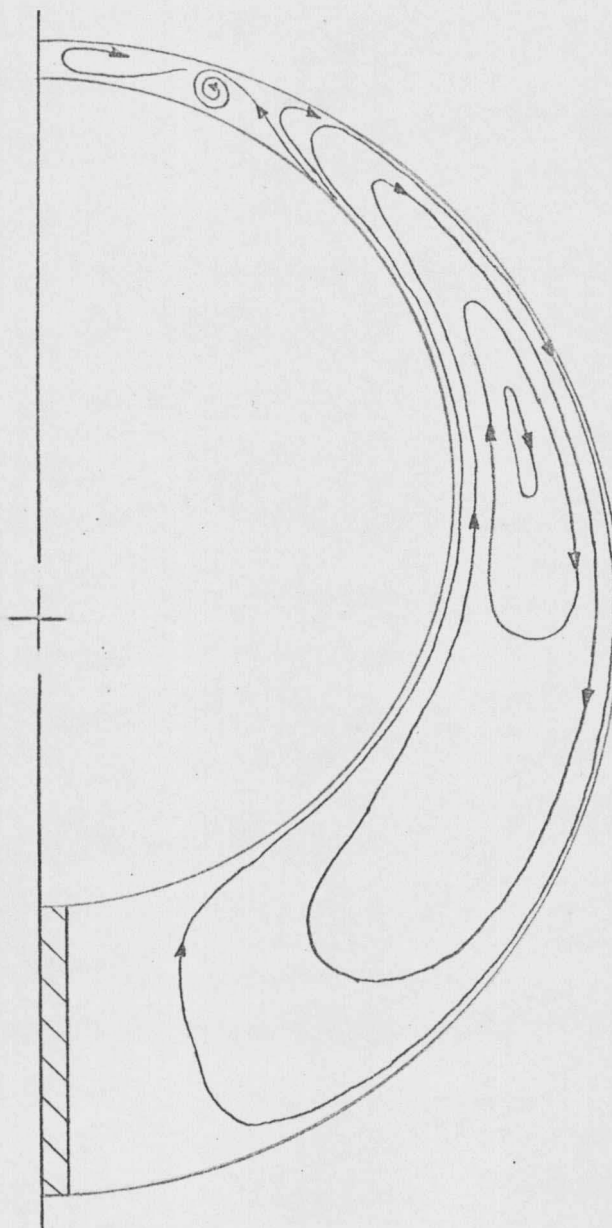


Figure 4.5 Sketch of +0.750 Eccentricity Air Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 27,000$$

$$\Delta T = 15^\circ F$$

fashion. For a greater Grashof number, the vortex region consisted of numerous counter-rotating cells, and these would occasionally be injected into the crescent-eddy flow. For very large temperature differences ( $\Delta T > 75^\circ\text{F}$ ), only the larger diameter vortices, as shown in Figure 4.6, were observed since the smoke became very diffused near the upper centerline. The small ones which earlier existed closer to the vertical centerline no longer appeared, but rather, a three-dimensional spiral motion resulted in this region. The upper region of the crescent-eddy pattern was periodically altered due to the shifting and shedding of the pair of vortex cells. This flow remained up to the maximum observed Grashof number of 126,000 ( $\Delta T = 87^\circ\text{F}$ ). Although the flow was very unsteady at the extreme top, the three-dimensional spiral flow, as described previously by Yin, et al [6, 10] had not yet developed near the main cell, but it appeared as though this condition would have undoubtedly resulted for a slightly greater Grashof number.

The next lower position studied (+0.375) at a minimum Grashof number of 18,000 ( $\Delta T = 9^\circ\text{F}$ ) was characterized by the random tangentially moving vortices in the upper region once again. As the imposed temperature difference was increased, these vortices were occasionally injected into the main flow as before. In the neighborhood of  $Gr_L = 70,000$  ( $\Delta T = 45^\circ\text{F}$ ), however, the upper vortex region became totally violent in nature, and a three-dimensional spiral flow resulted. This extremely unsteady motion caused the top portion of the crescent-eddy

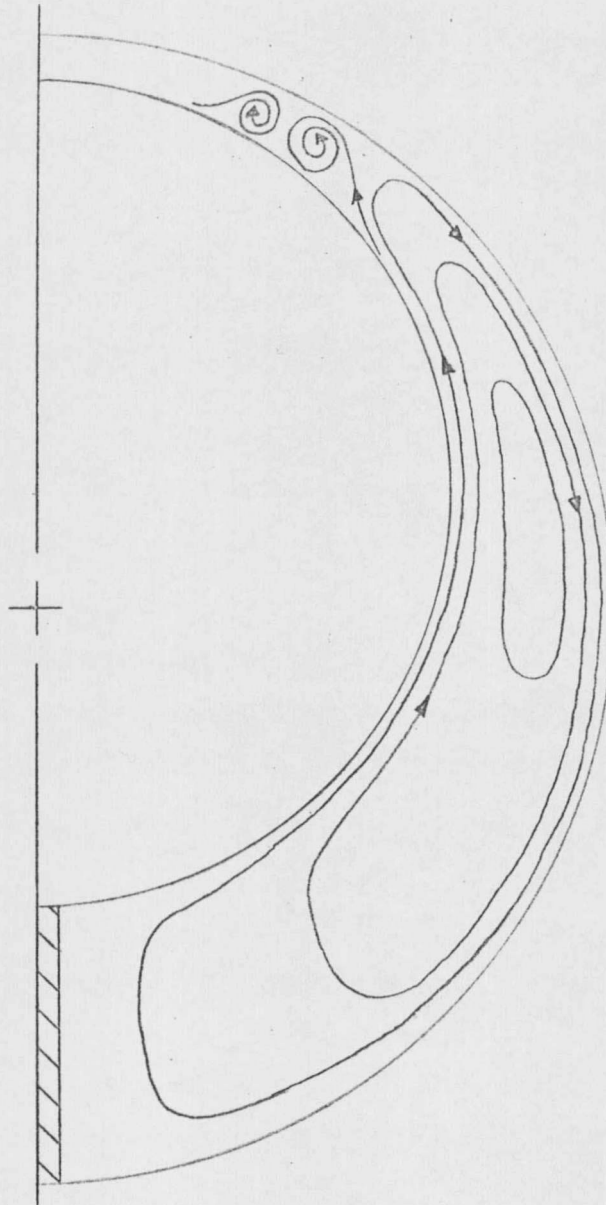


Figure 4.6 Sketch of +0.750 Eccentricity Air Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 108,000$$

$$\Delta T = 75^\circ F$$

to become completely indistinguishable.

The negative eccentricity of  $-0.375$  produced a steady flow pattern up to a Grashof number of about  $60,000$  ( $\Delta T = 38^\circ\text{F}$ ). Below this transition point, the observed flows were primarily of the crescent-eddy type. At very low temperature differences ( $\Delta T < 8^\circ\text{F}$ ), two counter-rotating cells were again seen. A slight increase in the temperature difference effectively expanded the crescent-eddy pattern until it completely filled the region previously occupied by the two vortices (Figure 4.7). Near and above the transition point, most of the upward flow appeared to separate from the inner body at an angle of about  $45^\circ$  with respect to its vertical axis. Vortex cells once again appeared within the upper region. These unsteady cells oscillated laterally within the gap and were constantly seen to be changing their direction of rotation as if they were aimlessly wandering about. As the Grashof number increased the motion within the vortex region rapidly increased, and the three-dimensional spiral pattern resulted.

The lowest eccentricity corresponding to  $-0.750$  yielded results which were virtually identical with those presented for the eccentricity of  $-0.375$ , the only basic difference being the geometry effect due to the lowering of the inner sphere.

GAP WORKING FLUID: SILICONE 350

The two inner-body configurations just described using air were also tested utilizing silicone 350 as the gap fluid. The eccentricity

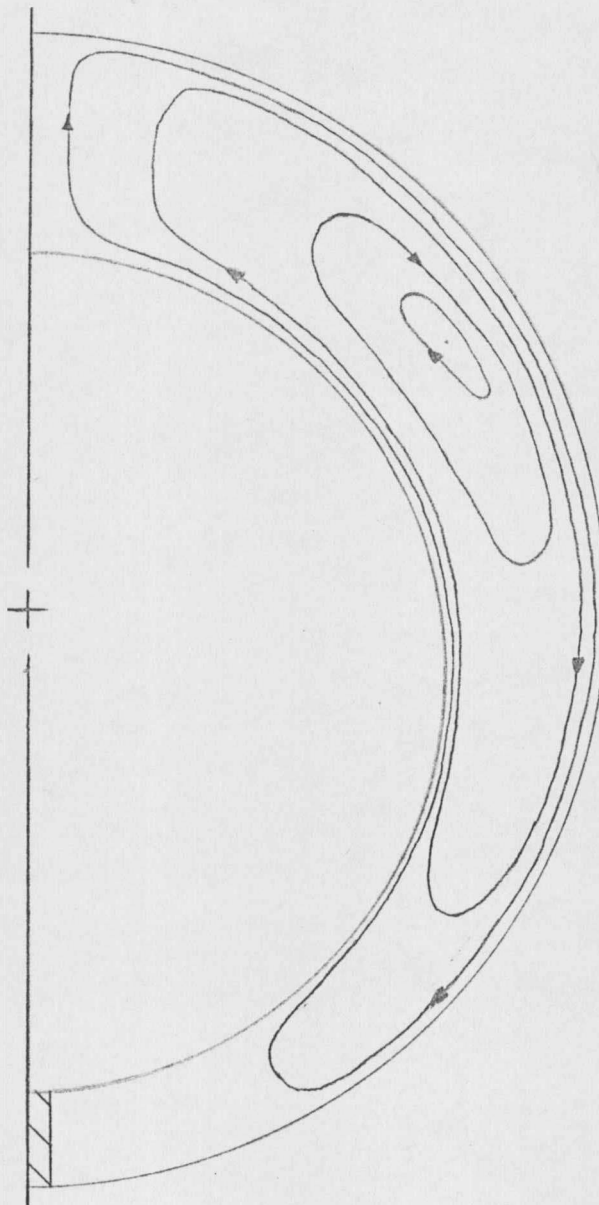


Figure 4.7 Sketch of -0.375 Eccentricity  
Air Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 24,000$$

$$\Delta T = 12^\circ F$$

values corresponded to those of the previous air studies.

The first eccentricity considered was +0.750. Figure 4.8 illustrates the flow pattern observed over the entire Grashof range examined ( $50 < Gr_L < 1200$ ,  $9^\circ F < \Delta T < 97^\circ F$ ) for the 4.50 inch sphere. No unsteadiness ever resulted within this range, and the flow pattern shown remained unaltered. The basic characteristics of the pattern were similar to those seen before. A thin high speed layer of fluid flowed upward and downward along the inner and outer spheres respectively, the upward moving fluid being turned at the chimney centerline as observed during the air investigations. From Figure 4.8 it can be seen that essentially zero motion occurs within the central portion of the flow pattern. Relatively long duration photographic time exposures (30 sec.) of the flow field have substantiated this observation.

The eccentricity value of +0.375 at Grashof numbers below 400 ( $\Delta T = 45^\circ F$ ) resulted in steady flow patterns similar to those of the previous case with the exception of a larger gap spacing found near the top region. At greater Grashof numbers, however, a rather periodic vortex flow was observed. In the neighborhood of the chimney where the flow direction was turned, short duration rotating cells appeared. The life of these cells for  $Gr_L = 425$  ( $\Delta T = 50^\circ F$ ) was only about 5 seconds, but they reappeared every 25 seconds. Figure 4.9 shows the rotating cells which were observed. It was noted that the frequency of reoccurrence increased as the Grashof number increased. For the

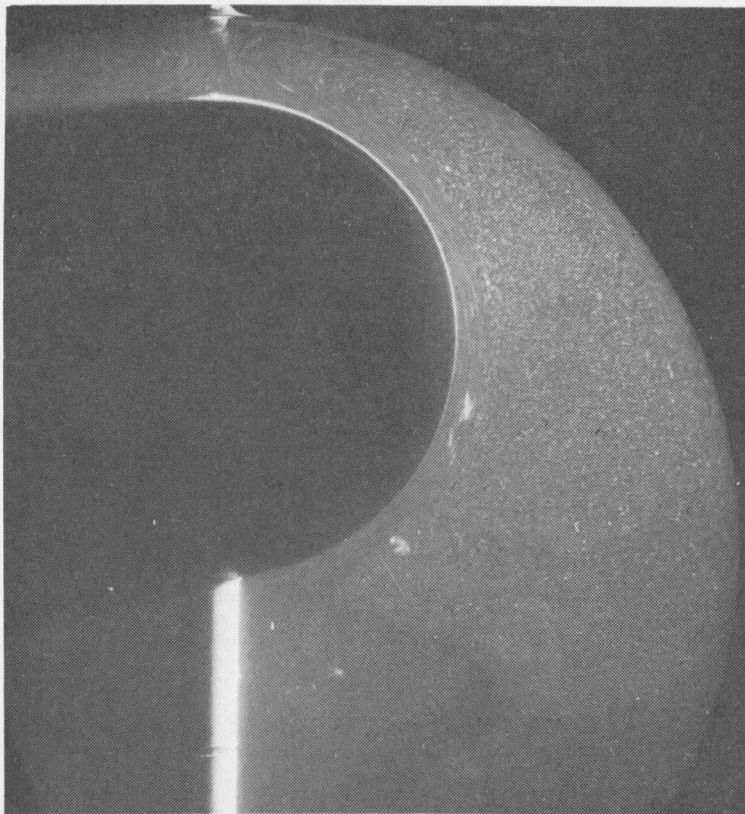


Figure 4.8 Photograph of +0.750 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 170$$

$$\Delta T = 23^\circ\text{F}$$

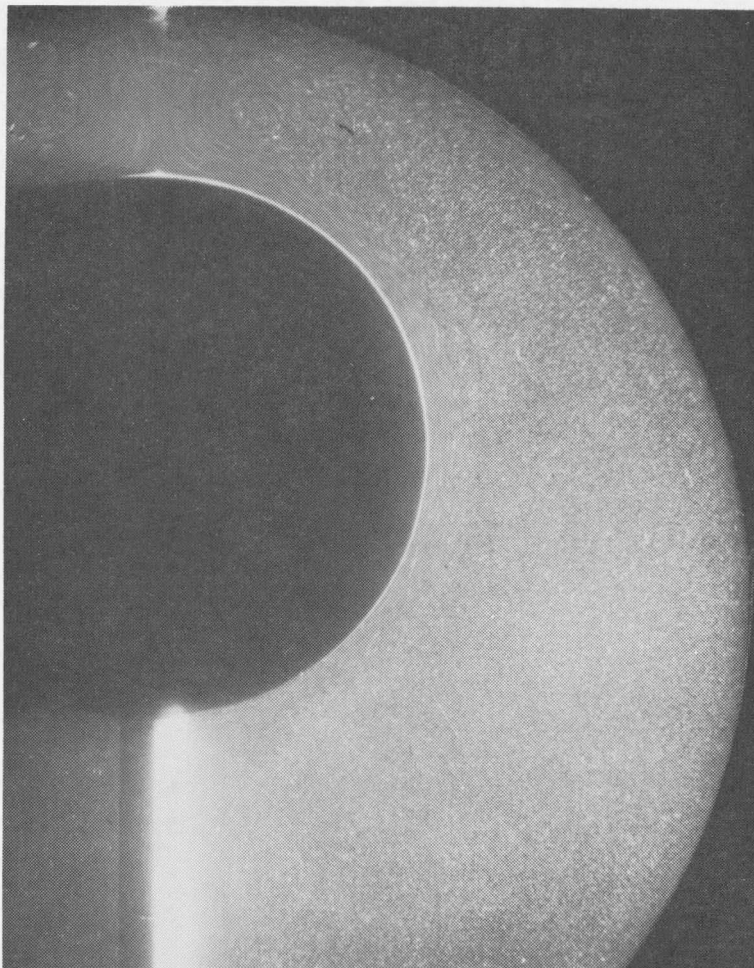


Figure 4.9 Photograph of +0.375 Eccentricity  
Silicone 350 Flow Pattern

$$D_o / D_i = 2.17$$

$$Gr_L = 425$$

$$\Delta T = 50^{\circ}F$$

maximum observed Grashof number value of 820 ( $\Delta T = 80^\circ\text{F}$ ), the period decreased to approximately 15 seconds.

The next lower eccentricity case of -0.375 indicated a steady flow pattern for the entire Grashof number range investigated. For  $Gr_L$  less than 350 the upward flow followed the contour of the inner sphere until it contacted the vertical thermal plume, at which time the fluid ascended to the outer sphere. Most of the fluid then returned downward via the outer sphere as it cooled. Some of the fluid contained within the high speed upward moving layer, however, was lost to the stagnant interior region along the chimney. Figure 4.10 indicates the motion observed. The flow lines which have been abruptly terminated in this sketch indicate that essentially zero velocity occurred at these points. Increasing the Grashof number above 350 ( $\Delta T = 39^\circ\text{F}$ ) yielded the rotating vortices pattern once again. This rotation was initiated along the inner body near the base of the chimney where the flow was directed upward. As the Grashof number was further increased ( $Gr_L > 350$ ), however, this rotation originated at greater angles when measured with respect to the center of the inner body and the upward vertical centerline. The rolling vortices, one on each side, then proceeded to climb up the chimney while entraining some of the fluid in the stagnant region as they did so. Once the vortices reached the top, they started moving outward in the direction of the high speed cooling layer and were very rapidly engulfed within it, thus losing their vortex identity.

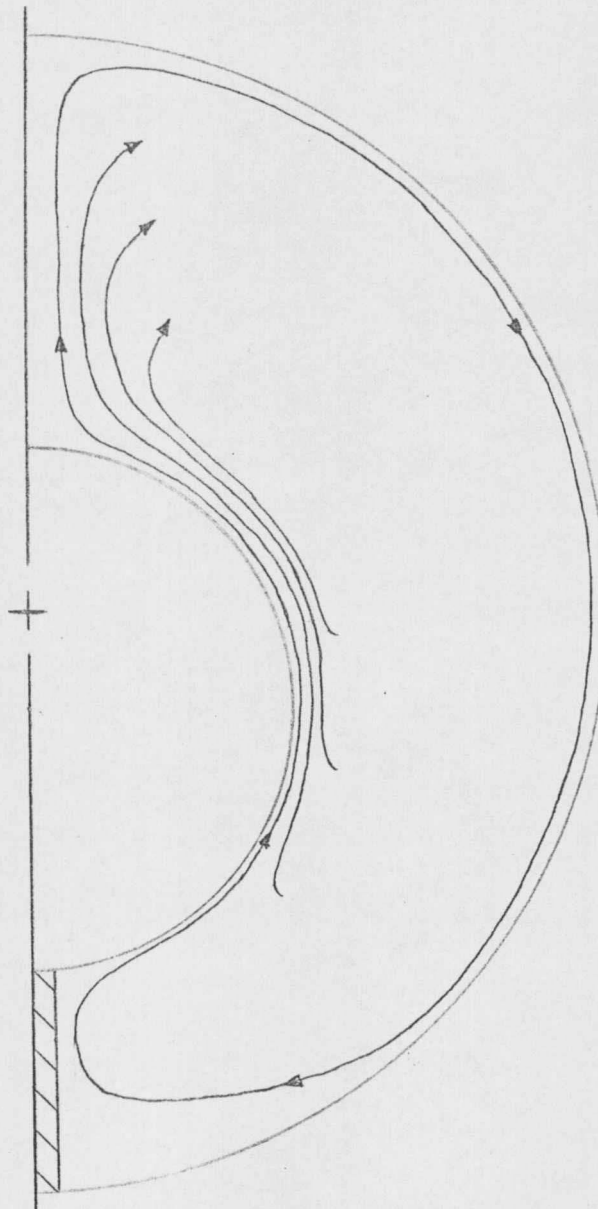


Figure 4.10 Sketch of -0.375 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 300$$

$$\Delta T = 37^\circ\text{F}$$

Figure 4.11 shows these vortices after they have progressed about half way up the plume. Again, the sequence of events just described appeared to be periodic in time. This flow condition prevailed up to a temperature difference of about 75°F at which time additional cells developed. Since these new cells were much more pronounced at the eccentricity of -0.750, the descriptions of them are presented later.

The minimum eccentricity of -0.750 for impressed temperature differences less than 40°F resulted in a flow pattern as illustrated by Figure 4.10 with the chimney length increased because of the accompanying geometry change. A slight increase in the Grashof number ( $Gr_L > 300$ ) again brought about the upward rotating vortex motion. For  $Gr_L > 800$  ( $\Delta T = 75^\circ F$ ), it was observed that the vortices, which earlier moved directly up the side of the chimney, now acquired some lateral motion and drifted into the stagnant region losing their strength. At this larger temperature difference, a greater mass of hot fluid was convected along the vertical centerline to the outer sphere. The inertia of this plume appeared responsible for producing two new rotating cells at the extreme upper region of the chimney (Figure 4.12). The vortices which migrated into the stagnant region were quickly replaced by new ones which emerged as a result of fluid turning upward as already mentioned. Unsteadiness occurred with this phenomenon, and the chimney, which was normally observed to be straight, now displayed a tangential wavy motion. This flow pattern was observed up to the maximum Grashof

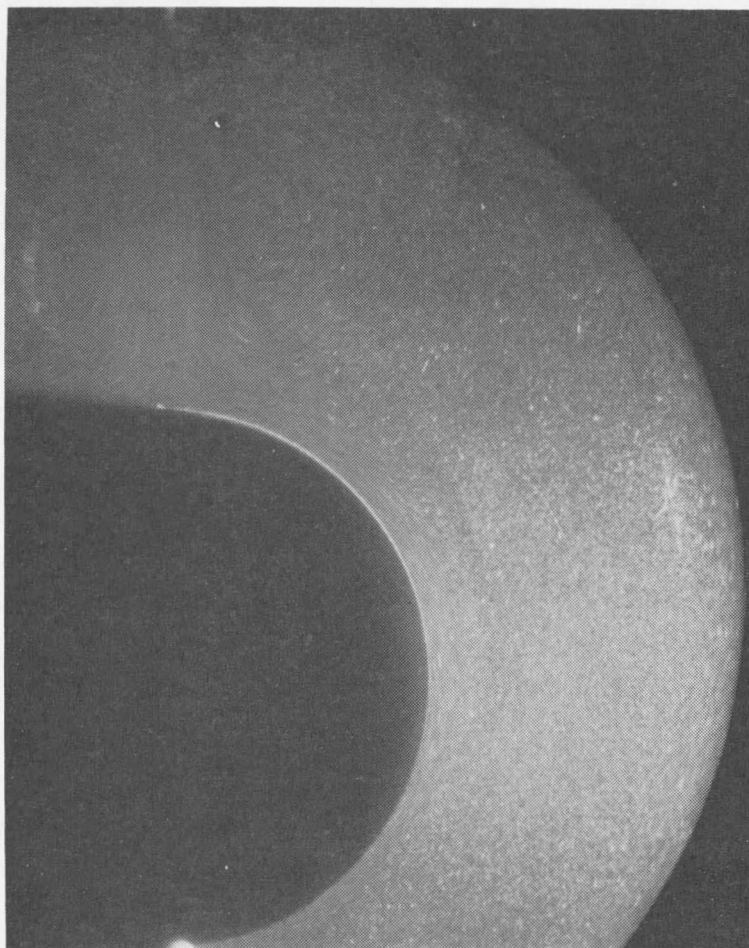


Figure 4.11 Photograph of -0.375 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 450$$

$$\Delta T = 50^\circ F$$

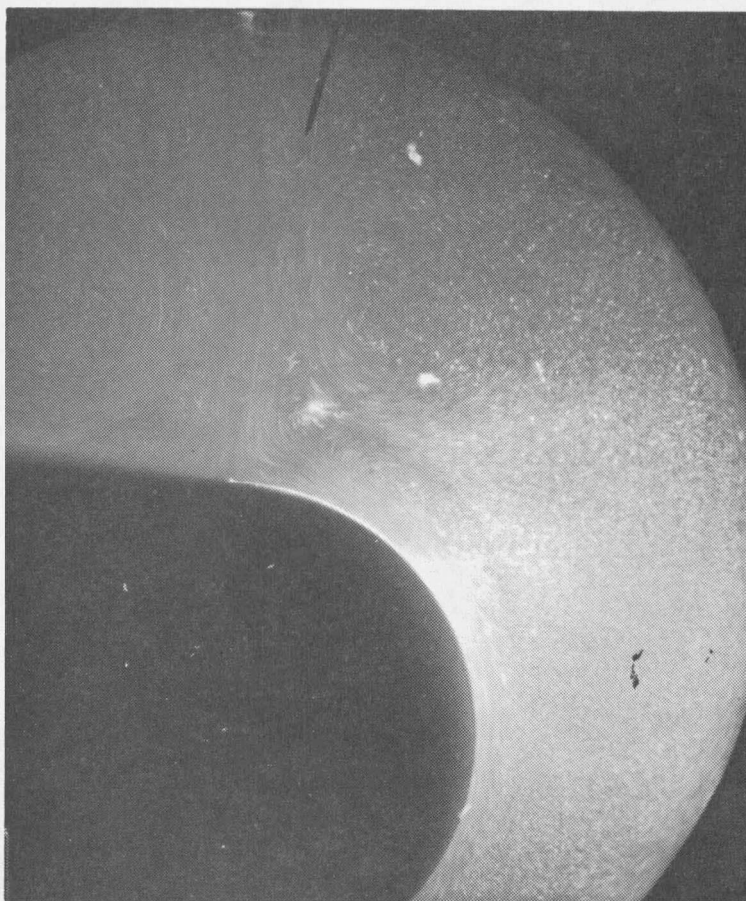


Figure 4.12 Photograph of -0.750 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 2.17$$

$$Gr_L = 800$$

$$\Delta T = 75^{\circ}F$$

number of 1050 ( $\Delta T = 86^\circ\text{F}$ ).

The next set of results considered the 7.00 inch spherical inner-body configuration with the eccentricity values remaining the same. Figure 4.13 is indicative of the +0.750 eccentricity flow patterns observed over the entire Grashof number range investigated ( $12 < Gr_L < 230$ ). This corresponded to a temperature difference ranging from  $15^\circ\text{F}$  to  $122^\circ\text{F}$ . Because the extremely narrow gap in the upper region was very difficult to study, the nature of the flow could not be truly determined at the lower Grashof numbers. For larger Grashof numbers though, it appeared as if there were numerous, randomly rotating three-dimensional vortices meandering about. Specifically, these seemed to be confined to within an annular spacing defined by the vertical centerline and a  $30\text{--}35^\circ$  angle measured from the center of the inner sphere. This unsteadiness never indicated any evidence of disturbing the primary crescent-eddy flow.

The gap spacing in the upper region was increased as a result of lowering the inner sphere and the concentric situation was studied. From the minimum observed Grashof value of 13 to a value of 100 ( $18^\circ\text{F} < \Delta T < 75^\circ\text{F}$ ), the flow patterns were noted to be the completely steady crescent types. Accompanied with a slight increase in the temperature difference, however, unsteadiness was initiated. Rotation of the flow field occurred on both sides of the chimney, and the boundary layer associated with the cooling fluid attained an undulating type motion.

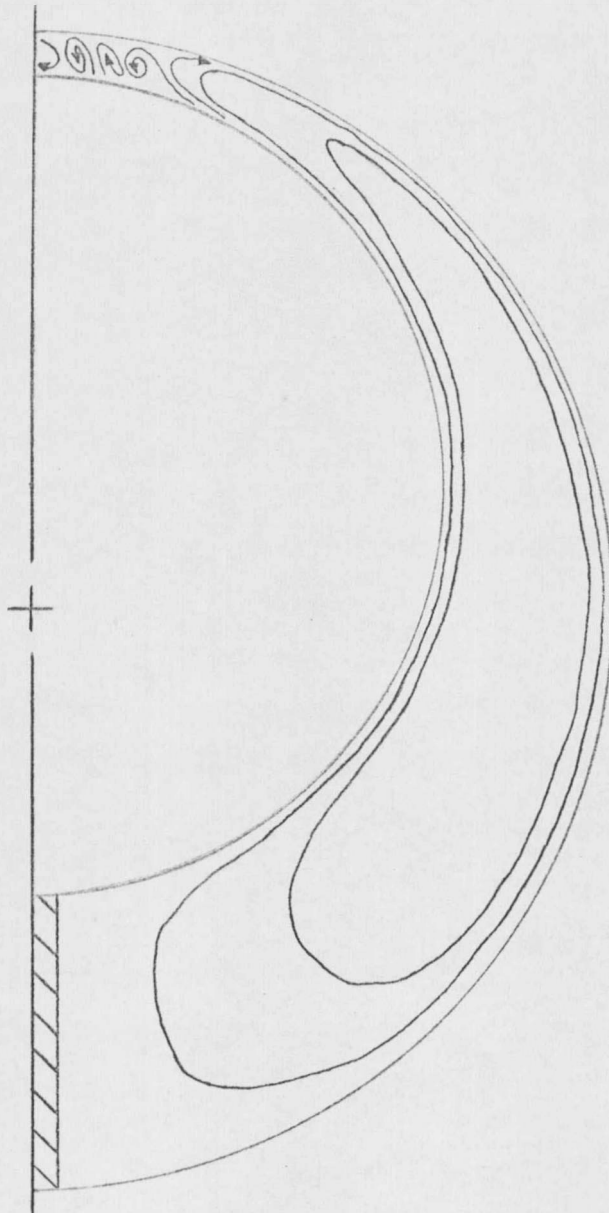


Figure 4.13 Sketch of +0.750 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 70$$

$$\Delta T = 61^\circ F$$

When the Grashof number reached a value of about 157 ( $\Delta T = 90^\circ\text{F}$ ), a portion of the upward moving fluid separated before contacting the chimney (Figure 4.14). As the fluid flowed upward along the inner sphere, it looked as if unsteady tendencies were exhibited prior to separation. This type of fluid motion prevailed up to  $Gr_L = 327$  ( $\Delta T = 132^\circ\text{F}$ ).

At this point, an attempt to describe the fluid motion which would have resulted for the +0.375 eccentricity case is presented. Drawing upon the known fundamental details of the flow patterns previously documented for the surrounding cases, the following postulation is given. From the observations made thus far, there appears to be some criterion which governs the influence of the unsteady vortex flow on the main crescent which always exists. As the upper gap region becomes narrower, as it does for increasing positive eccentricity cases, only smaller diameter vortices can physically exist. These smaller vortices lack the strength of larger ones and hence cannot exert nearly as significant an effect on the primary main crescent. These vortices are therefore primarily restrained to the relatively narrow upper portion of the gap. It does seem quite likely, however, that some of these will be shed upon the main crescent, and, for large Grashof numbers, a three-dimensional vortex flow will result near the top. With the smaller gap, there undoubtedly has to be flow separation along the inner sphere depending on the impressed temperature difference. For the relatively

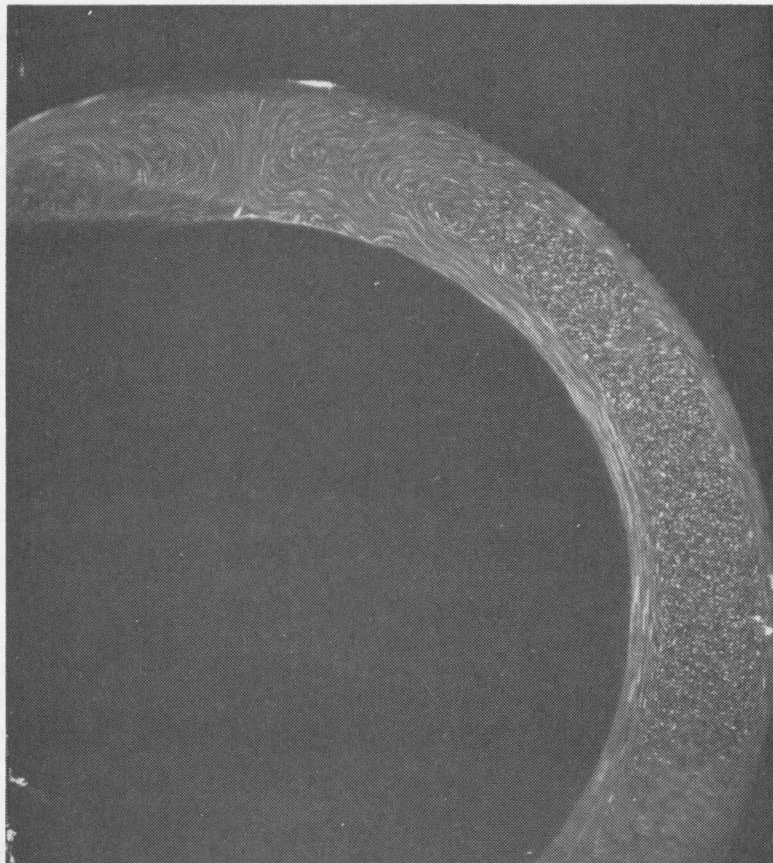


Figure 4.14 Photograph of Concentric Silicone  
350 Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 160$$

$$\Delta T = 90^\circ F$$

low Grashof numbers, separation was found to occur at about  $35^\circ$  for the +0.750 situation while it did not occur for the concentric case. This  $35^\circ$  angle was measured from the upper vertical centerline and the center of the inner sphere. It seems highly likely therefore that an eccentricity of +0.375 would have a separation angle located somewhere in the neighborhood of  $20^\circ$ . Flow separation tendencies resulted since the fluid, which completely followed the inner body contour at low temperature differences, suffered a loss of momentum. Consequently, the adverse pressure gradient assisted separation.

The negative eccentricity of -0.375 produced the crescent-eddy type flows as discussed in most of the previous geometries reported. At a Grashof number of about 45, the onset of unsteadiness appeared. Rotation adjacent to the chimney developed, and, as the Grashof number increased to 70 ( $\Delta T = 60^\circ\text{F}$ ), these rotating cells drifted away from the vertical centerline flow in a somewhat random fashion but returned a short time later. The photograph in Figure 4.15 illustrates the pattern which occurred when the cells were removed from the thermal plume. A significant increase in the temperature difference ( $\Delta T > 90^\circ\text{F}$ ) led to a condition of rather unpredictable convective unsteadiness as typified by Figure 4.16. A random generation of new vortex cells resulted, and this type of flow pattern was observed up to the maximum observed Grashof number of 270 ( $\Delta T = 120^\circ\text{F}$ ).

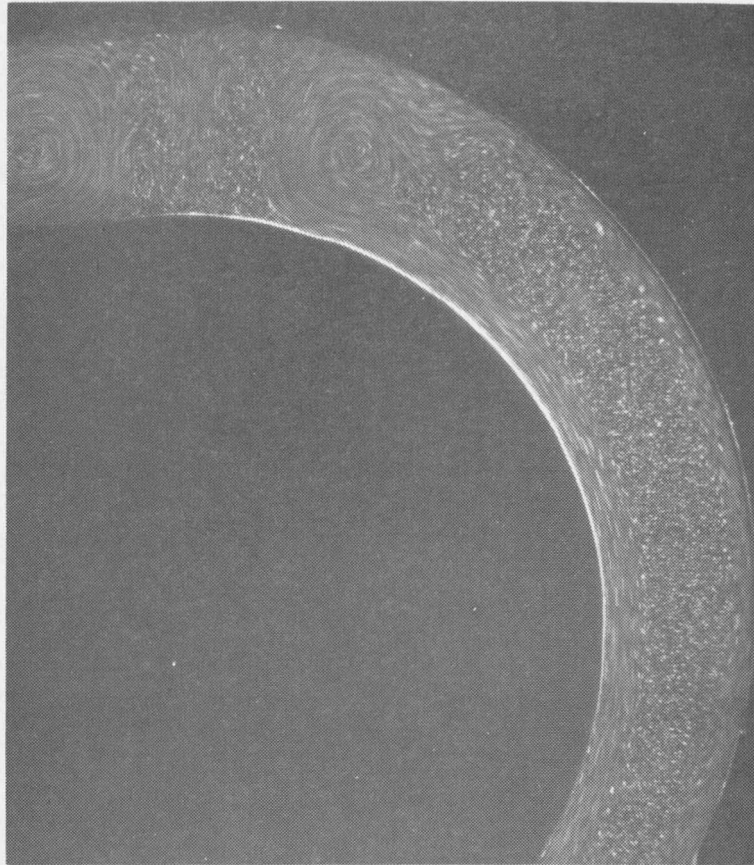


Figure 4.15 Photograph of -0.375 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 70$$

$$\Delta T = 60^\circ\text{F}$$

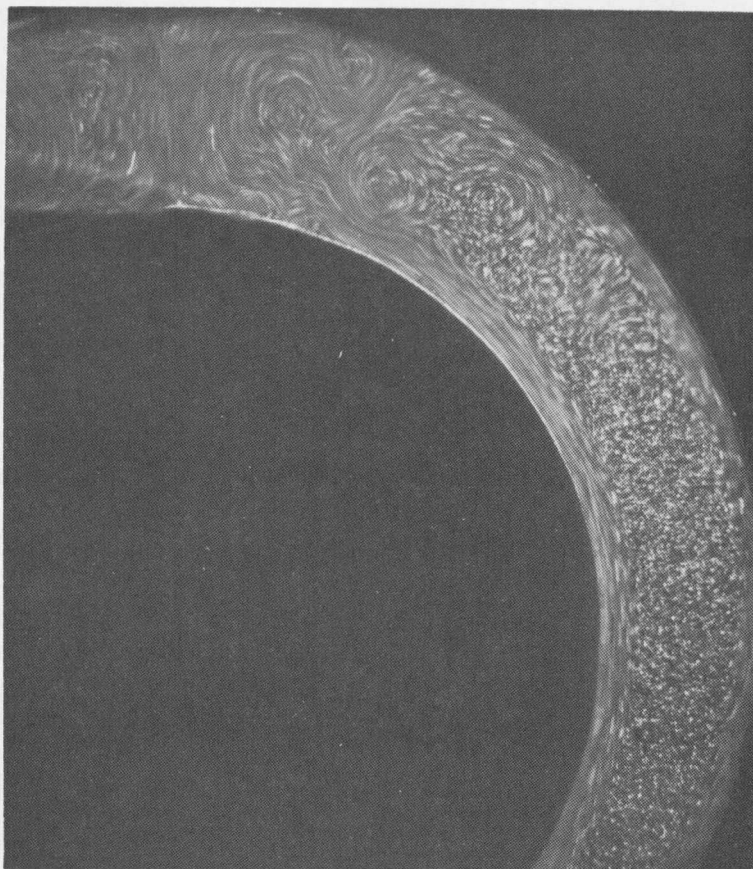


Figure 4.16 Photograph of -0.375 Eccentricity  
Silicone 350 Flow Pattern

$$D_o/D_i = 1.40$$

$$Gr_L = 268$$

$$\Delta T = 118^\circ\text{F}$$

The last eccentric configuration tested was that of  $-0.750$ . Once more the pure crescent-like flow pattern resulted for Grashof numbers less than about 15. The unsteady flow fields caused by the increase in the Grashof number followed exactly the order of events outlined for the last case ( $\epsilon = -0.375$ ).

## CONCENTRIC CYLINDER FLOW PATTERN DESCRIPTIONS

The cylinder results included in this section describe first the flows observed using 350 cs silicone oil as the gap medium followed by the water flow pattern experimental results. Since past investigators have expressed the Grashof numbers for cylinder flows based on a length parameter defined as the difference between the radius of the enclosing outer sphere and the cylinder's radius, the same notation has been accepted herein. The fluid properties contained within this section have been evaluated using the arithmetic mean temperature. This is convenient for comparison of the flow results with the temperature profile results published by earlier investigators since they also employed the arithmetic mean temperature.

## GAP WORKING FLUID: SILICONE 350

The first cylinder tested (4.50 x 6.50 inches) had an aspect ratio of 1.44 and was operated for a minimum Grashof number of 32 ( $\Delta T = 6^\circ\text{F}$ ). Figure 4.17 illustrates the steady flow pattern which resulted. This basic motion was maintained essentially intact until the Grashof number reached 400, at which time counter-rotating vortices emerged in the flow field in the vicinity of the chimney (Figure 4.18). Also noted at this greater temperature difference was the appearance of some secondary interior flow not previously encountered. A sketch of this flow pattern (Figure 4.19) has been provided to more clearly indicate the fluid movement witnessed in Figure 4.18. When the Grashof

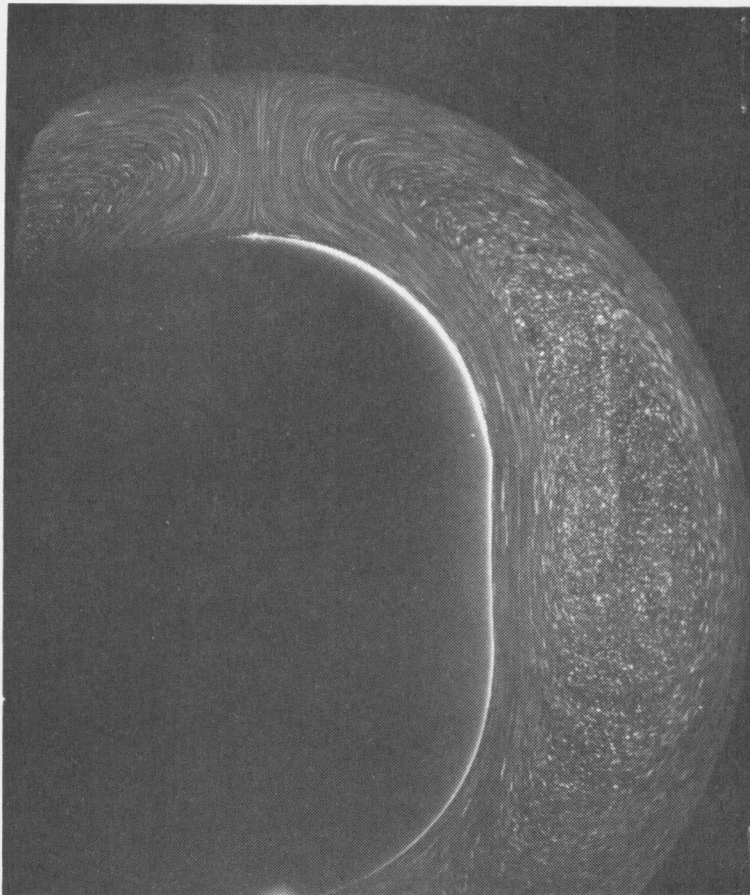


Figure 4.17 Photograph of 4.50x6.50 inches  
Cylinder Flow Pattern (Silicone 350)

Aspect Ratio = 1.44

$$Gr_L = 32$$

$$\Delta T = 6^\circ\text{F}$$

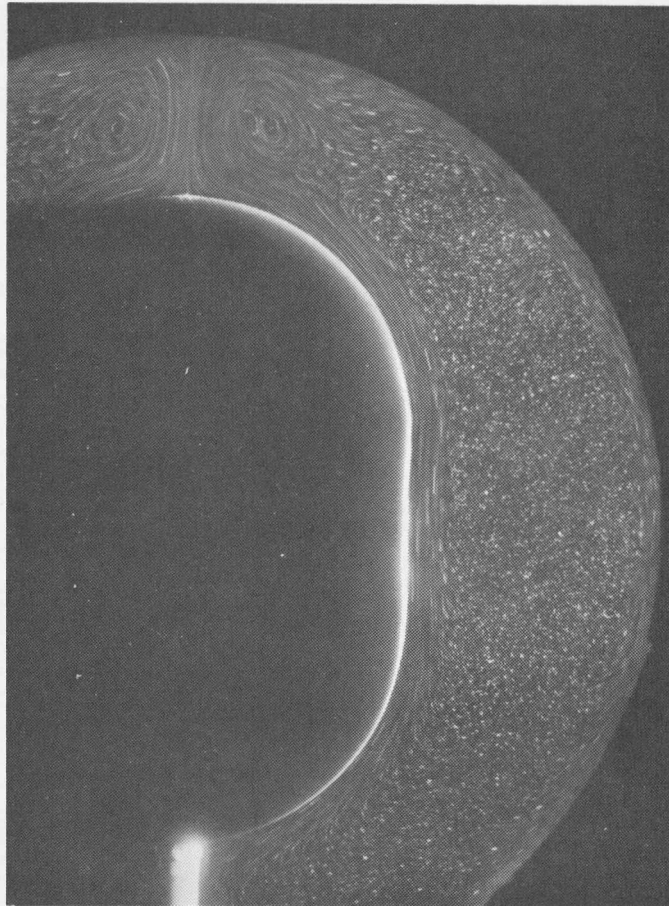


Figure 4.18 Photograph of 4.50x6.50 inches Cylinder Flow Pattern (Silicone 350)

Aspect Ratio = 1.44

$Gr_L = 450$

$\Delta T = 50^\circ F$

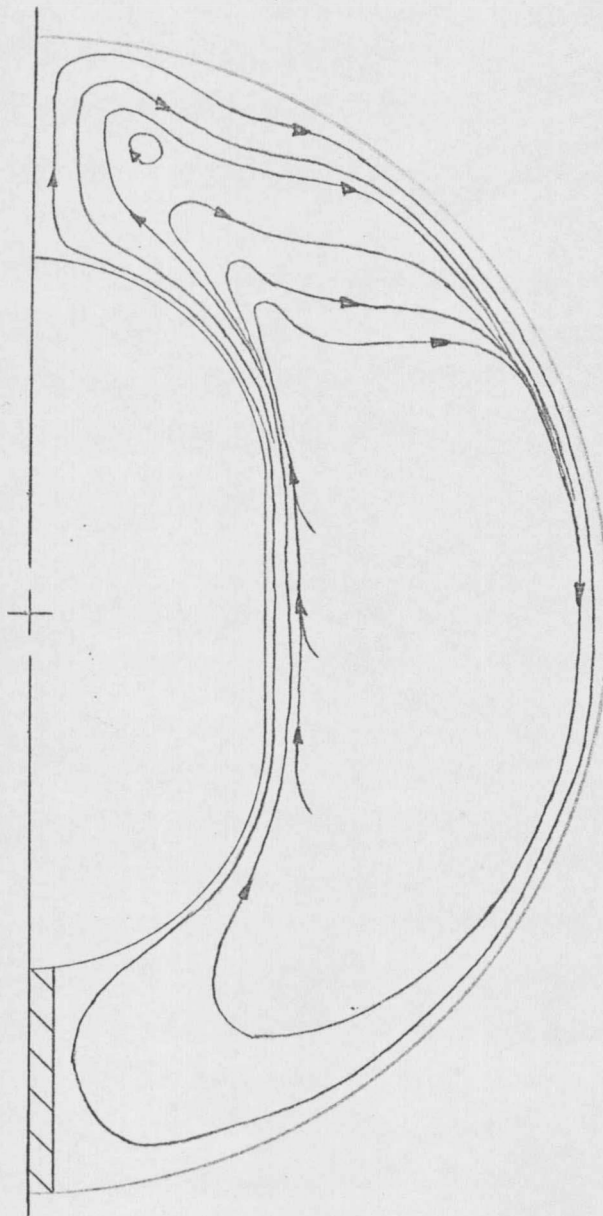


Figure 4.19 Sketch of 4.50 x 6.50 inches  
Cylinder Flow Pattern (Silicone 350)

Aspect Ratio = 1.44

$Gr_L = 450$

$\Delta T = 50^\circ F$

number attained a value greater than about 900, unsteadiness developed. The typical events which characterized this motion discussed in the eccentric sphere studies were exhibited. These included 1) the random migration of the vortex cells away from the thermal plume, 2) the wavy motion of the high speed cool fluid as it receded from the top portion of the chimney, and 3) the continually changing points of vortex formation as the fluid flowed upward along the inner body toward the chimney. This type of unsteadiness persisted for the remainder of the Grashof range considered ( $Gr_{L,max} = 4700$ ,  $\Delta T = 160^\circ F$ ).

The next cylindrical body investigated contained a much longer vertical section between its hemispherical ends. The size of this body was 4.50 x 8.50 inches yielding an aspect ratio of 1.89. For relatively low Grashof numbers ( $75 < Gr_L < 300$ ,  $13^\circ F < \Delta T < 37^\circ F$ ), steady flow patterns as depicted in Figure 4.20 were observed. An increase in the Grashof number ( $Gr_L > 300$ ) led to a condition where flow separation became quite distinct. As shown in Figure 4.21, separation occurred just after the fluid started to follow the contour of the upper hemispherical end. The extreme upper region of the gap where the chimney was usually seen became unsteady. This unsteadiness became more pronounced at the greater temperature differences. The maximum observed Grashof number was 4300, which corresponded to  $\Delta T = 147^\circ F$ .

The last geometry consisted of a 7.00 x 9.00 inches cylindrical

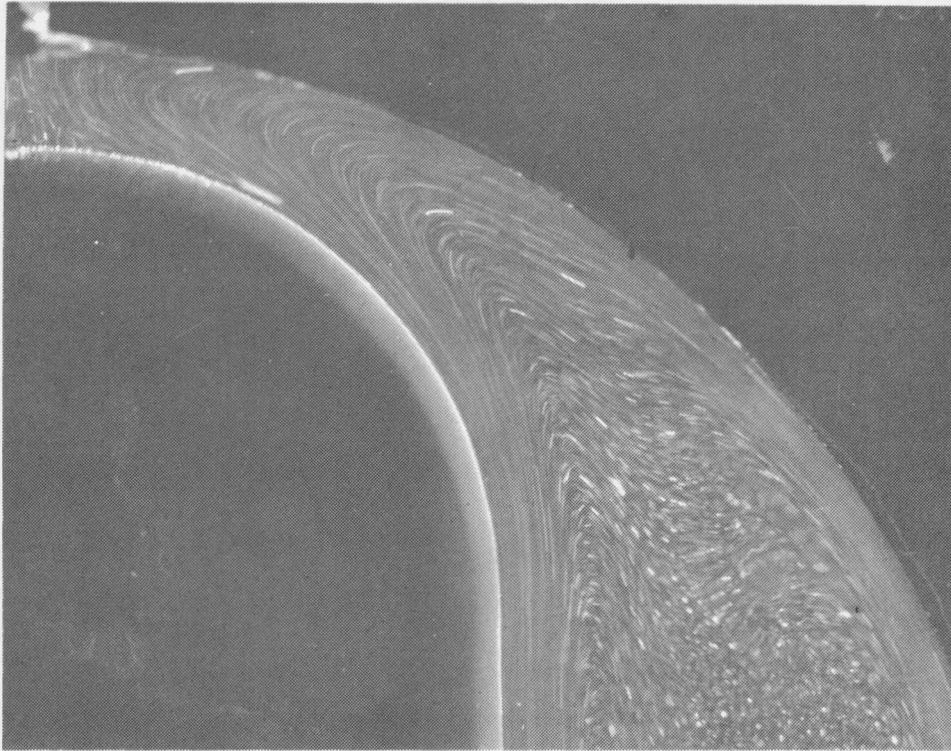


Figure 4.20 Photograph of 4.50x8.50 inches Cylinder Flow Pattern (Silicone 350)

Aspect Ratio = 1.89

$Gr_L = 170$

$\Delta T = 26^\circ F$

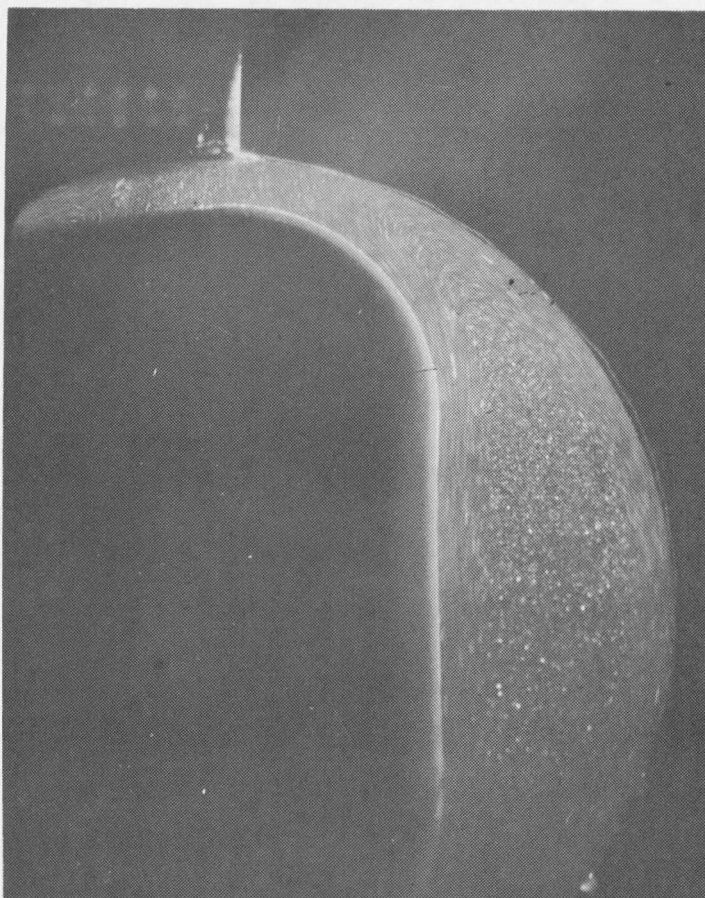


Figure 4.21 Photograph of 4.50x8.50 inches  
Cylinder Flow Pattern (Silicone 350)

Aspect Ratio = 1.89

$Gr_L = 330$

$\Delta T = 41^\circ F$

inner body with an aspect ratio of 1.29. For this case, no significant change in the flow pattern appeared over the entire Grashof range tested ( $7 < Gr_L < 290$ ). As was found earlier for the eccentric spheres, flow separation was seen to impede the upward moving fluid from entering the narrow gap region at the top. Consequently, the bulk of the upward fluid flowed toward the outer sphere. For all of the flows analyzed, unsteady motion was detected in the neighborhood of the vertical centerline. Since the tracer particle movement in this region did not photograph very well and was almost impossible to follow by eye, the exact nature of the unsteadiness was very difficult to determine. It generally appeared, however, that small vortices were randomly drifting about with three-dimensional flow characteristics. Figure 4.22 illustrates the basic fluid motion displayed for this configuration.

#### GAP WORKING FLUID: WATER

The 4.50 x 6.50 inches cylinder flow pattern was characterized by 1) the high speed primary peripheral flow, 2) the secondary interior flow, and 3) the central stagnant region for most of the temperatures differences imposed ( $875,000 < Gr_L < 99,000,000$ ). Figures 4.23 and 4.24 are included to aid in understanding the details of the fluid motion observed. The formation of a distinct interior cell occurred between the upward high-speed fluid and the central stagnant region at the transition of the vertical cylinder section and the top hemi-

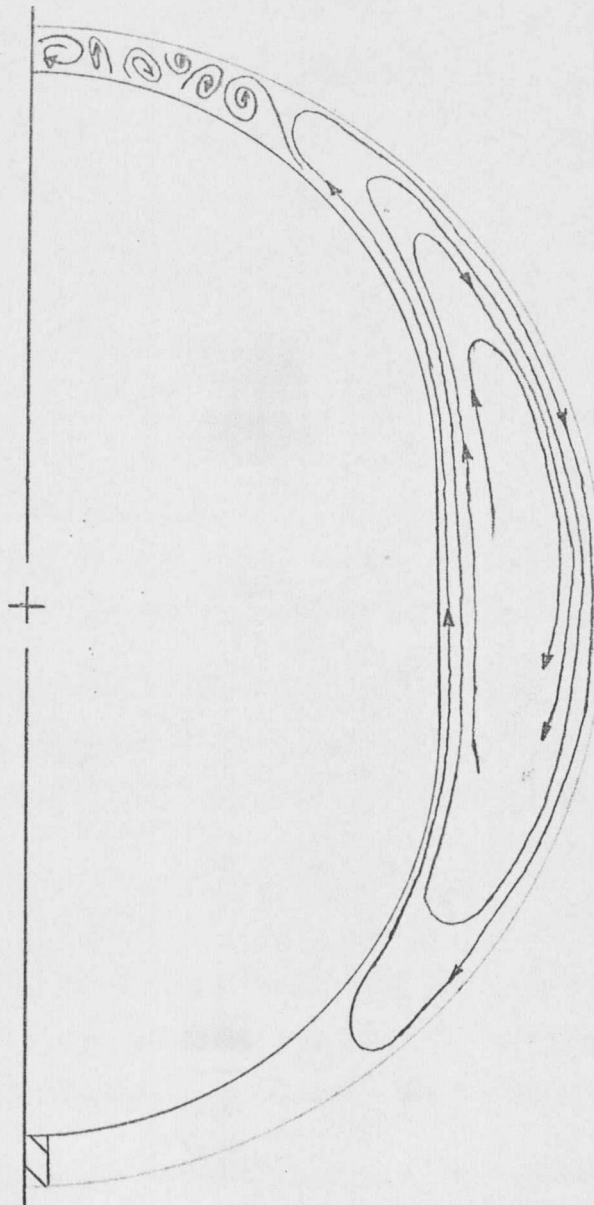


Figure 4.22 Sketch of 7.00 x 9.00 inches  
Cylinder Flow Pattern (Silicone 350)

Aspect Ratio = 1.29

$$Gr_L = 166$$

$$\Delta T = 97^\circ F$$

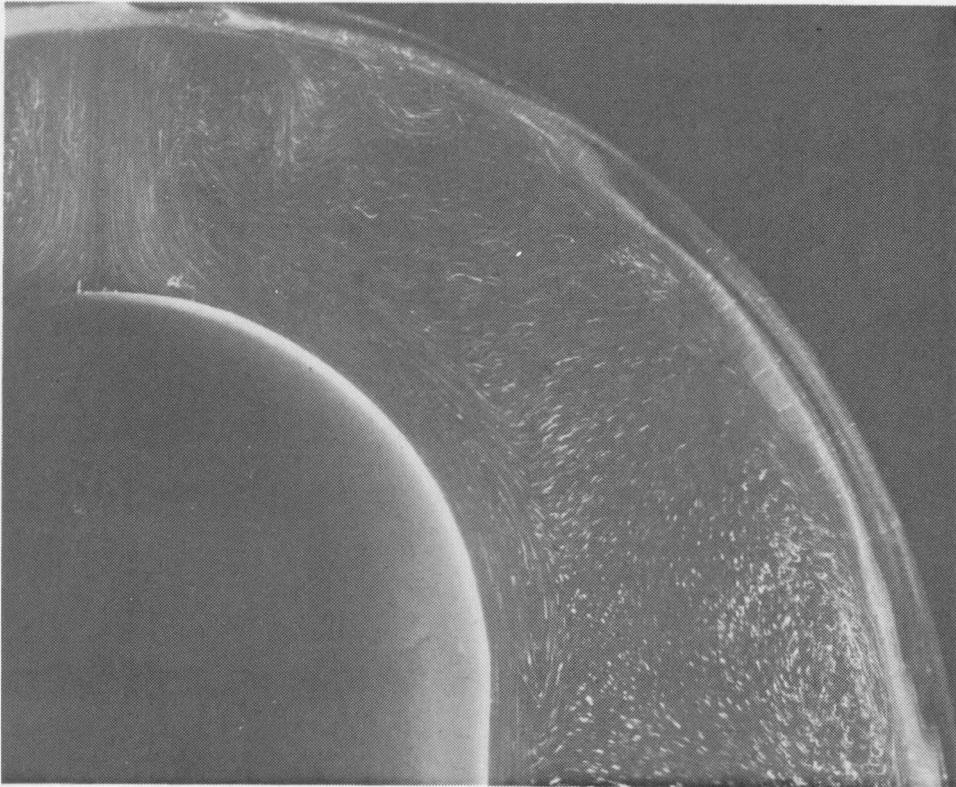


Figure 4.23 Photograph of 4.50x6.50 inches Cylinder  
Flow Pattern

Aspect Ratio = 1.44

$Gr_L = 54,000,000$

$\Delta T = 56^\circ F$

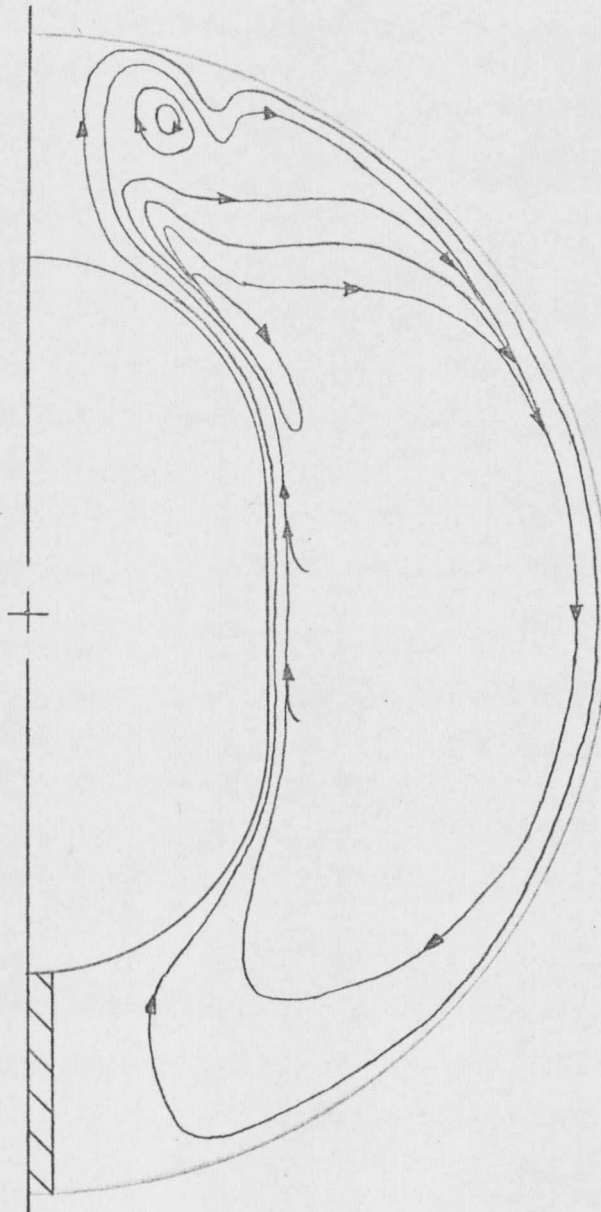


Figure 4.24 Sketch of 4.50 x 6.50 inches  
Cylinder Flow Pattern (Water)

Aspect Ratio = 1.44

$Gr_L = 54,000,000$

$\Delta T = 56^\circ F$

spherical end. The flow field generally remained steady except for the cases of relatively large temperature differences where some unsteadiness was associated with 1) the interior secondary flow and 2) the vortices which were shed downward along the outer sphere.

The longest cylindrical inner body (4.50 x 8.50 inches) utilized yielded a steady flow pattern for Grashof numbers ranging from 850,000 to about 7,000,000 ( $9^{\circ}\text{F} < \Delta T < 27^{\circ}\text{F}$ ). The sketch provided in Figure 4.25 outlines the typical flow observed. For larger Grashof numbers, however, the onset of unsteadiness occurred in the chimney region. This unsteadiness strengthened itself with increases in the temperature difference, and, at the maximum examined value of  $\text{Gr}_L = 159,000,000$  ( $\Delta T = 89^{\circ}\text{F}$ ), three-dimensional vortex motion resulted. These vortices were randomly shed downward into the upper half of the stagnant region.

The last configuration involved a 7.00 x 9.00 inches cylinder. The Grashof number range extended from 70,000 to 850,000 ( $9^{\circ}\text{F} < \Delta T < 65^{\circ}\text{F}$ ). The flow field observed for this situation was almost identical to that described for the silicone 350 used with this inner body. The only change was that, for the smaller temperature differences, the main crescent-eddy extended further into the narrow gap near the chimney for the water results. The same unsteadiness previously mentioned appeared near the centerline.

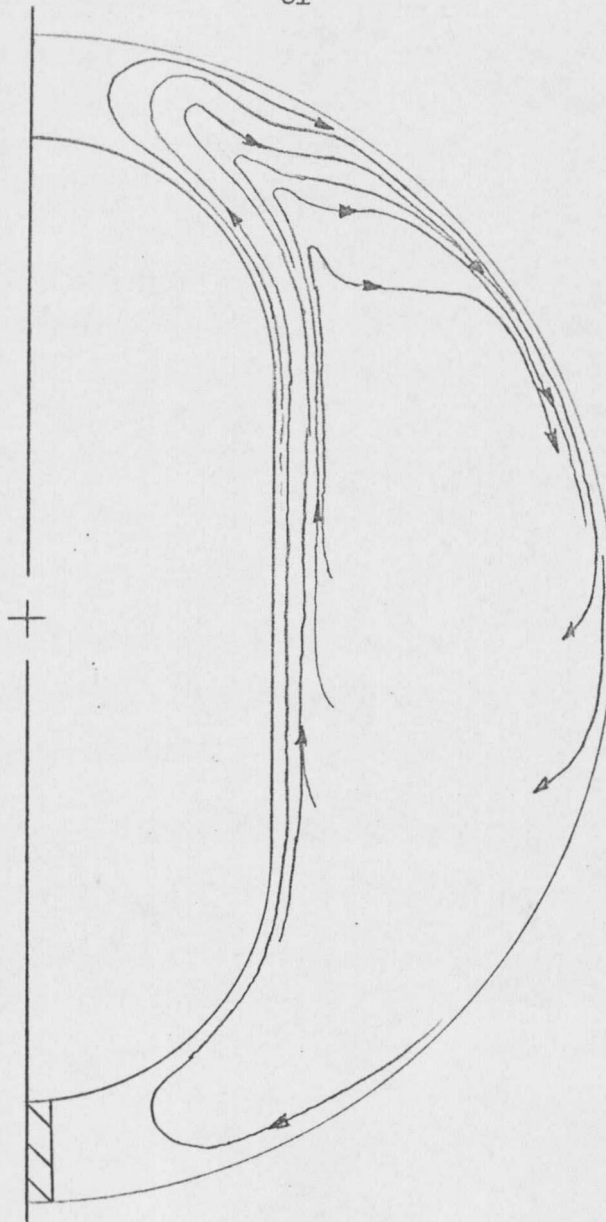


Figure 4.25 Sketch of 4.50 x 8.50 inches  
Cylinder Flow Pattern (Water)

Aspect Ratio = 1.89

$Gr_L = 7,000,000$

$\Delta T = 27^\circ F$

## SUMMARY AND DISCUSSION OF RESULTS

A brief overall summary of the results are presented since this should benefit work involved with future correlations. The experimental results have therefore been compiled and provided in tabular form. Contained within the following tables (Table 4.1 - 4.6) are all of the cases investigated. Caution is urged in interpreting the numerical values, however. The transition region Grashof numbers, which differentiate between the steady and unsteady observed flow fields, are suggested to be in the vicinity of those values cited. It is quite reasonable, though, to expect a 10-20% deviation for transition occurrence since the onset of unsteadiness in many instances was questionable. Reference is also made indicating the basic types of flow patterns and unsteadiness observed for the various flow regimes.

The bulk of the eccentric air results obtained in this study were found to be very similar to those of concentric spheres previously documented [3, 6, 8, 10]. The configuration corresponding to  $D_o/D_i = 2.17$  was generally indicative of the crescent-eddy and kidney-shaped-eddy flow patterns over the entire Grashof number range examined ( $100,000 < Gr_L < 1,000,000$ ). The major features of these flow patterns being 1) the thin high speed fluid layers traveling upward and downward immediately adjacent to the inner and outer spheres respectively, 2) the upper vertical centerline chimney region, and 3) the central low speed

TABLE 4.1  
SUMMARY OF ECCENTRIC AIR RESULTS ( $D_o/D_i = 2.17$ )

| Eccentricity | Steady Flow Regime*                                                                       | Unsteady Flow Regime**                                                                       |
|--------------|-------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| +0.750       | $92,000 < Gr_L < 160,000$<br>$64,000 < Ra_L < 112,000$<br>Crescent-Eddy                   | $160,000 < Gr_L < 907,000$<br>$112,000 < Ra_L < 635,000$<br>Falling-Vortices -- 3-D Spiral   |
| +0.375       | $110,000 < Gr_L < 700,000$<br>$77,000 < Ra_L < 525,000$<br>Crescent-Eddy -- Kidney-Shaped | $700,000 < Gr_L < 970,000$<br>$525,000 < Ra_L < 680,000$<br>Interior Expansion & Contraction |
| -0.375       | $100,000 < Gr_L < 750,000$<br>$70,000 < Ra_L < 525,000$<br>Crescent-Eddy -- Kidney-Shaped | $750,000 < Gr_L < 850,000$<br>$525,000 < Ra_L < 595,000$<br>Interior Expansion & Contraction |
| -0.750       | $94,000 < Gr_L < 750,000$<br>$65,800 < Ra_L < 525,000$<br>Crescent-Eddy                   | $750,000 < Gr_L < 842,000$<br>$525,000 < Ra_L < 590,000$<br>Interior Expansion & Contraction |

\* The first number appearing in this column represents the minimum observed value.

\*\* The last number appearing in this column represents the maximum observed value.

TABLE 4.2  
SUMMARY OF ECCENTRIC AIR RESULTS ( $D_o/D_i = 1.40$ )

| Eccentricity | Steady Flow Regime*                                                                                       | Unsteady Flow Regime**                                                                  |
|--------------|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| +0.750       | $14,000 < Gr_L < 75,000$<br>$9,800 < Ra_L < 49,000$<br>Crescent-Eddy<br>(except from top near centerline) | $75,000 < Gr_L < 126,000$<br>$49,000 < Ra_L < 88,500$<br>Falling-Vortices -- 3-D Spiral |
| +0.375       | $18,000 < Gr_L < 70,000$<br>$12,600 < Ra_L < 42,000$<br>Crescent-Eddy                                     | $70,000 < Gr_L < 115,000$<br>$42,000 < Ra_L < 80,500$<br>Falling-Vortices -- 3-D Spiral |
| -0.375       | $12,500 < Gr_L < 70,000$<br>$8,700 < Ra_L < 49,000$<br>Crescent-Eddy                                      | $70,000 < Gr_L < 120,000$<br>$49,000 < Ra_L < 84,000$<br>Falling-Vortices -- 3-D Spiral |
| -0.750       | $13,000 < Gr_L < 60,000$<br>$9,000 < Ra_L < 42,000$<br>Crescent-Eddy                                      | $60,000 < Gr_L < 118,000$<br>$42,000 < Ra_L < 82,000$<br>Falling-Vortices -- 3-D Spiral |

TABLE 4.3  
SUMMARY OF ECCENTRIC SILICONE 350 RESULTS ( $D_o/D_i = 2.17$ )

| Eccentricity | Steady Flow Regime                                                                            | Unsteady Flow Regime**                                                                         |
|--------------|-----------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| +0.750       | $50 < Gr_L < 1,200^{**}$<br>$200,000 < Ra_L < 3,250,000$<br>Crescent-Eddy                     | not present                                                                                    |
| +0.375       | $170 < Gr_L < 820^{**}$<br>$660,000 < Ra_L < 2,670,000$<br>Crescent-Eddy -- Periodic-Vortices | not present                                                                                    |
| -0.375       | $130 < Gr_L < 920$<br>$535,000 < Ra_L < 2,800,000$<br>Crescent-Eddy -- Periodic Vortices      | $920 < Gr_L < 1,050$<br>$2,800,000 < Ra_L < 3,200,000$<br>Climbing-Vortices (chimney waviness) |
| -0.750       | $135 < Gr_L < 920$<br>$550,000 < Ra_L < 2,800,000$<br>Crescent-Eddy -- Periodic-Vortices      | $920 < Gr_L < 1,050$<br>$2,800,000 < Ra_L < 3,200,000$<br>Climbing-Vortices (chimney waviness) |

TABLE 4.4  
SUMMARY OF ECCENTRIC SILICONE 350 RESULTS ( $D_o/D_i = 1.40$ )

| Eccentricity | Steady Flow Regime*                                                                                  | Unsteady Flow Regime**                                                                    |
|--------------|------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| +0.750       | $15 < Gr_L < 229$<br>$60,000 < Ra_L < 555,000$<br>Crescent-Eddy<br>(except from top near centerline) | $15 < Gr_L < 229$<br>$60,000 < Ra_L < 555,000$<br>Falling-Vortices -- 3-D Spiral          |
| +0.375***    | $13 < Gr_L < 70$<br>$54,000 < Ra_L < 225,000$<br>Crescent-Eddy                                       | $70 < Gr_L < 325$<br>$225,000 < Ra_L < 700,000$<br>Falling-Vortices -- 3-D Spiral         |
| -.0375       | $12 < Gr_L < 45$<br>$50,000 < Ra_L < 160,000$<br>Crescent-Eddy                                       | $45 < Gr_L < 270$<br>$160,000 < Ra_L < 620,000$<br>Lateral Vortex Drift -- Multi-Vortices |
| -.0750       | $13 < Gr_L < 20$<br>$52,000 < Ra_L < 80,000$<br>Crescent-Eddy                                        | $20 < Gr_L < 95$<br>$80,000 < Ra_L < 285,000$<br>Lateral Vortex Drift -- Multi-Vortices   |

\*\*\* postulated case

TABLE 4.5  
SUMMARY OF CYLINDER RESULTS (SILICONE 350)

| Cylinder Size<br>(inches) | Steady Flow Regime*                                                                                | Unsteady Flow Regime**                                                                                     |
|---------------------------|----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| 4.50x6.50                 | $32 < Gr_L < 900$<br>$136,000 < Ra_L < 2,500,000$<br>Crescent-Eddy -- Secondary Flow               | $900 < Gr_L < 4,700$<br>$2,500,000 < Ra_L < 8,600,000$<br>Lateral Vortex Drift                             |
| 4.50x8.50                 | $75 < Gr_L < 300$<br>$300,000 < Ra_L < 1,000,000$<br>Crescent-Eddy -- Secondary Flow               | $300 < Gr_L < 4,300$<br>$1,000,000 < Ra_L < 7,800,000$<br>2 & 3-Dimensional Vortices                       |
| 7.00x9.00                 | $7 < Gr_L < 290$<br>$31,000 < Ra_L < 650,000$<br>Crescent-Eddy<br>(excluding upper portion of gap) | $7 < Gr_L < 290$<br>$31,000 < Ra_L < 650,000$<br>2 & 3-Dimensional Vortices<br>(upper portion of gap only) |

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region. The unsteadiness, which was prevalent for  $Gr_L > 700,000$ , was usually characterized by interior expansions and contractions. This pulsating type motion imposed a continuous radial shifting motion on the peripheral flow lines. The largest eccentricity of +0.750, however, resulted in unsteadiness associated with falling-vortices [8] and three-dimensional spiral flows [10]. This form of unsteadiness normally occurred when 1) the gap width became sufficiently narrow, and 2) when a significant temperature difference was applied.

The diameter ratio of 1.40 utilizing air clearly displayed the basic crescent-eddy flow pattern for all of the eccentricities considered ( $12,000 < Gr_L < 70,000$ ). For larger Grashof numbers ( $Gr_L > 70,000$ ,  $\Delta T > 45^\circ F$ ), the integrity of the low Grashof number flows was altered as a result of flow unsteadiness attributed to the falling-vortices and the three-dimensional spiral effects generated in the upper portion of the gap.

The eccentric silicone 350 portion of this investigation revealed some new types of flow characteristics. The 4.50 inch inner sphere ( $D_o/D_i = 2.17$ ) generally yielded a peripheral steady flow pattern which maintained the basic crescent shape. The same flow features seen with the air were observed except for the low speed region seen with air. This region utilizing silicone 350 appeared almost totally stagnant. For negative eccentricities, additional convective activity developed. This phenomenon substantiated the suspicions of past

investigators working with the heat-transfer apparatus only [5]. Periodic vortices, which originated in that region where the angular flow turned to traverse up the chimney, appeared. These vortices, one on each side of the thermal plume, rotated upward along the chimney with the same direction of rotation as the main crescent flow pattern. Once these vortices reached the outer sphere, they were entrained by the high speed cooling layer which flowed downward along the outer sphere. The unsteadiness which occurred for this geometric configuration was primarily restricted to the negative eccentricity cases where convective motion was enhanced. The climbing-vortices, which were periodic for Grashof numbers less than about 900, lost their periodicity and appeared randomly at higher Grashof numbers. Waviness of the chimney was also noted for the larger impressed temperature differences.

Utilizing silicone 350, the diameter ratio of 1.40, which corresponded to the 7.00 inch inner sphere, generally resulted in the crescent-shaped peripheral flow patterns for low Grashof numbers (Table 4.4). For the cases involving the positive eccentricities, where a relatively narrow gap existed in the upper flow field region, falling-vortices and three-dimensional vortices were believed to have appeared. Because the very narrow gap was generally very difficult to study, some doubt as to the true nature of the flow in this region existed. Since the silicone is so very viscous and the absolute fluid velocities small, the unsteadiness generated within this region

was severely damped when contact was established with the main crescent-like flow. Consequently, these unsteady flows and their effects were primarily constrained to the upper gap region. Negative eccentricities on the other hand exhibited flow unsteadiness characterized by 1) lateral vortex drifting, 2) undulating tendencies of the high speed cooling layer, 3) continual relocation of the flow separation angle on the inner body, and 4) the formation of multiple vortex cells. A general observation regarding the unsteady flow regime associated with this configuration is that as the eccentricity was decreased (displaced further below the concentric position), larger diameter and greater strength vortices resulted. These vortices are then apparently much more capable of penetrating the relatively stagnant region thereby inducing the "multi-vortices" flow pattern which was observed.

The cylinder flow results using silicone 350 as the test fluid for the aspect ratios of 1.44 and 1.89 yielded flow patterns very similar to those witnessed for the eccentric sphere studies. The peripheral flow, which appeared as an elongated crescent with a straight section, remained undisturbed for low Grashof numbers. The upper range of the Grashof numbers listed in the steady regime of Table 4.5 led to the appearance of secondary flows. These rather weak secondary return flows were usually observed to flow in the opposite direction of the hot upward moving fluid for a short distance, but then drifted horizontally toward the outer sphere.

Unsteadiness, for all of the cylinders studied, was once again found to be rather proportional to the gap spacing present, although, the temperature difference was still significant. For those cylinders which permitted only very narrow gap widths in the upper region (aspect ratios of 1.29 and 1.89), the onset of two and three dimensional vortex flows again are believed to have resulted. The unsteadiness exhibited by the 1.44 aspect ratio cylinder for  $Gr_L > 900$  can best be described by the lateral vortex drift adjacent to the chimney as described earlier.

The cylindrical investigations using water as the gap medium generally resulted in steady flow patterns with weak secondary return flows as discussed previously in the literature for concentric sphere studies [8, 10]. These flows were primarily representative of the 1.44 and the 1.89 aspect ratio cylinders only. For these two cases, a vortex cell pair, one on each side of the chimney, characterized most of the Grashof number range. A distinct interior cell was observed for these configurations. The weak secondary return flow in conjunction with the upward vertical hot flow along the inner body formed this cell near the top portion of the straight cylindrical section.

The form of unsteadiness followed that described for the silicone fluid. Falling-vortices, which were shed tangentially downward along the outer sphere, and three-dimensional vortices, found near the centerline, often appeared.

The effect of cylinder length, which is described in terms of aspect ratio, was found to have perhaps a very slight influence on the shape of the flow patterns but this effect was hardly noticeable. For low Grashof numbers, no flow separation tendency characteristics appeared in comparison to the included eccentric sphere studies or the works reported by others [10]. For larger Grashof number flows, where the upward vertical moving fluid had achieved additional momentum, separation-like characteristics of the outer layers may have occurred which aided in reinforcing the secondary flows in that neighborhood. Since the outer sphere cooling return flows and the secondary flows are often in the vicinity of where one might expect a separation effect due to a relatively large aspect ratio, the conclusion here is that no appreciable cylinder effect could be observed on the flow pattern.

The Prandtl number effect can be analyzed by considering the flow characteristics of the different fluids tested. This investigation, which examined a Prandtl number range extending from 0.7 to 4148, has clearly illustrated that the typically basic flow patterns observed for air have the same characteristics as those observed for silicone 350. Although for higher viscosity fluids the unsteadiness was constrained to relatively small local regions, the peripheral flow, which was crescent-like in shape, always appeared. Consequently, no major viscosity effects resulted.

The correlation of the observed flows for this study are essentially in agreement with the temperature profiles previously reported [5, 11]. Since all of the flow patterns observed were composed of five elementary flow characteristics which determined the general shape of these profiles, it was concluded that the basic flow field which resulted was quite independent of small applied temperature differences. These five basic regions are 1) the two thin high velocity fluid layers where convection heat transfer was the dominate mode of energy transport, 2) a central stagnant region dominated by conduction heat transfer, and 3) two regions of transition from the high to low velocity fluids. The temperature profiles can be physically interpreted with respect to these five regions just mentioned. With the high heat flux at the inner body boundary, hot fluid in this vicinity was rapidly convected away. As a result, a larger drop in temperature took place in a very short radial distance. This same type of effect was true of the outer thin cooling layer also. Therefore, these regions of the temperature profiles are ones of relatively steep temperature gradients. The flat portion of the temperature profile curve, where very little fluid motion was observed, generally had a slight temperature drop associated with it, and this was due to conduction. The remaining transition regions of the temperature profiles are possessed with both convection and conduction heat transfer characteristics. Illustrated in Figure 4.26 is a typical temperature profile discussed above. As

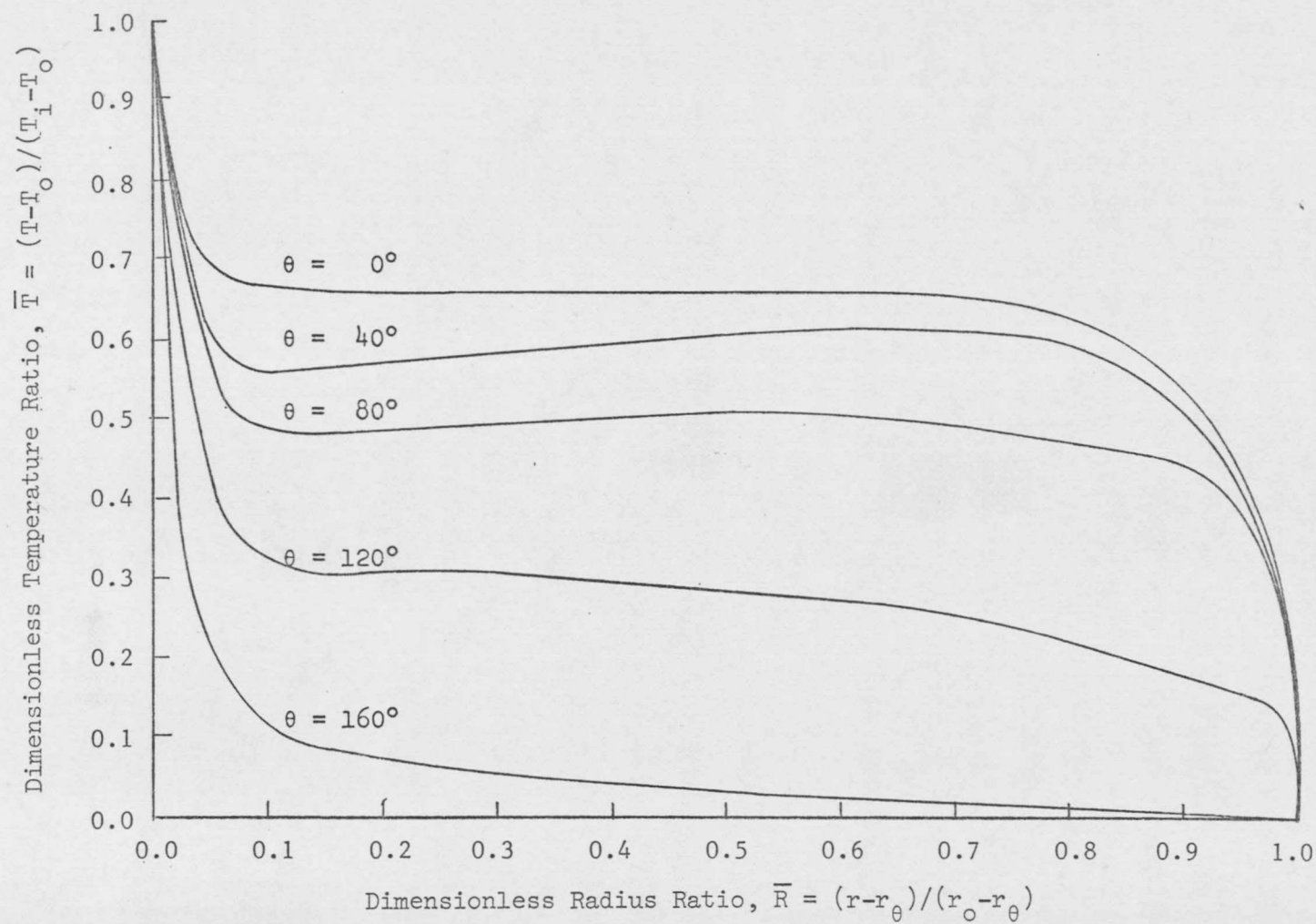


Figure 4.26 Temperature Profiles for the 7.00 inch Sphere (Water) [9]  
 $\varepsilon = -0.50$   $\Delta T = 40^\circ\text{F}$

shown for typical low Grashof number flows, the magnitudes of the  $0^\circ$ ,  $40^\circ$ ,  $80^\circ$ ,  $120^\circ$ , and  $160^\circ$  temperature profile curves, measured from the upward vertical axis, result in descending position as illustrated. This occurs since the colder fluid occupies the lower regions of the gap. In certain instances, however, it has been found that many times the  $0^\circ$  and  $40^\circ$  probes have yielded profiles lower than corresponding to the  $80^\circ$  probe. This phenomena has been explained by the existence of counter-rotating cells which have caused fluid near the inner boundary to become partially cooled and therefore allowing a much greater temperature drop on these profiles. The counter-rotating cell of the air studies was documented in the past for concentric air studies and was further substantiated in this work for the eccentric air studies. Liquid test fluids, when subjected to extremely small gaps and relatively high impressed temperature differences, have produced numerous temperature profiles with the  $0^\circ$  temperature profile lower than the  $40^\circ$  or  $80^\circ$  profiles. Since possible two-dimensional, unsteady vortex, multicellular structured flows were generally thought to be observed for such cases, the same explanation appears to be valid.

Temperature inversions also appeared in some of the profiles considered, but, since all flows basically resembled all others, the importance of this phenomena has been discounted somewhat. It suffices to say that it did result in the profiles and extensive discussions of this effect have been given by other authors [3, 5, 9, 11].

## CHAPTER V

### CONCLUSIONS AND RECOMMENDATIONS

The flow visualization apparatus previously used for air and water concentric sphere studies was extended to utilize a silicone oil test fluid and, also, to incorporate eccentric sphere and cylindrical inner-body geometries. The results obtained during this investigation have been found helpful for further understanding of some of the fundamentals associated with convective flow fields. One obvious overall result was that for the variety of fluids used and for relatively low temperature differences imposed, one basic flow pattern always existed. This pattern generally exhibited high speed peripheral flows which normally outlined the geometry of the configuration at hand. Unsteadiness of any real significance could be said to have occurred usually in the upper vertical centerline region. The effect of this unsteadiness upon the lower portion of the gap was found to decrease as the Prandtl number increased.

The effect of downward eccentricity of the inner spheres enhanced convective activity since a greater percentage of the gap became influenced by vortex flows. Vortices were found to have a penetrating effect on regions where little fluid motion had previously been observed.

Virtually no aspect ratio effect could be determined in this

investigation for the cylinders used. It seems that if such an effect were to be realized, a larger diameter enclosing sphere must be implemented. This is the situation since the upward flows along the vertical cylinders in this study were influenced by secondary return flows and by the near boundary of the outer sphere.

One recommendation for future related flow studies would be to investigate how to optimize the "quality" of tracer particles observed in the water and silicone test fluids because improper mixtures yield poor photographic results. Another possible consideration for additional work should perhaps be centered around studying and photographing those conditions where extremely narrow gaps exist. One problem frequently encountered during this study was that of many times being unable to definitely determine the true flow for such situations.

## APPENDIX

```

1.  C....  I = FLUID NUMBER          AIR          = 1
2.  C      WATER                     = 2
3.  C      SILICONE 350              = 3
4.  C....  CP(T,I) = SPECIFIC HEAT AT CONSTANT PRESSURE OF A SPECIFIED TEST FLUID
5.  C....  VIS(T,I) = ABSOLUTE VISCOSITY OF A SPECIFIED TEST FLUID
6.  C....  COND(T,I) = THERMAL CONDUCTIVITY OF A SPECIFIED TEST FLUID
7.  C....  RHO(T,I) = DENSITY OF A SPECIFIED TEST FLUID
8.  C....  BETA(T,I) = EXPANSION COEF. OF A SPECIFIED TEST FLUID
9.  C....  OD = OUTER DIAMETER (IN)
10. C....  ID = INNER DIAMETER (IN)
11. C....  BAROMETRIC PRESSURE (IN HG)
12. C....  AP = ATMOSPHERIC PRESSURE (LBF/SQ IN)
13. C....  GAP = DISTANCE BETWEEN THE INNER AND OUTER CONFIGURATIONS (IN)
14. C....  GR = GRASHOF NUMBER
15. C....  RA = RAYLEIGH NUMBER
16. C....  MM = NUMBER OF THERMOCOUPLES ON THE INNER BODY
17. C....  MMM = NUMBER OF THERMOCOUPLES ON THE OUTER BODY
18.      REAL ID, IR, IT, ITAVG
19.      INTEGER RUN
20.      DIMENSION OT(20),IT(20),E(20),DEV(20)
21.  C....  JJ = NO OF DATA RUNS
22.      DO 500 JJ=1,26
23.      READ(105,10) I, RUN, MM, MMM
24.      10  FORMAT(4I3)
25.      READ(105,11) OD, ID, ECC
26.      11  FORMAT(3F9.4)
27.      WRITE(108,50) RUN
28.      50  FORMAT('1','RUN NO. = ',I3)
29.      IF(I.EQ.1) GO TO 100
30.      IF(I.EQ.2) GO TO 101
31.      WRITE(108,51)
32.      51  FORMAT(' ',///,'FLUID .... SILICONE 350 CS')
33.      GO TO 102
34.      100 WRITE(108,52)

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35.      52 FORMAT(' ',///,'FLUID .... AIR')
36.      GO TO 102
37.      101 WRITE(108,53)
38.      53 FORMAT(' ',///,'FLUID .... WATER')
39.      102 CONTINUE
40.      DIAR = OD/ID
41.      GAP = (OD-ID)/2.
42.      ECCR = ECC/GAP
43.      WRITE(108,54) 'OD,ID,ECC,DIAR,ECCR'
44.      54 FORMAT('0','OUTER DIA. = ',F10.4,' INCHES',//,'INNER DIA. = ',
45.      $F10.4,' INCHES',//,'ECCENTRICITY = ',F10.4,///,'DIA. RATIO = ',F
46.      $10.4,///,'ECC. RATIO = ',F10.4,////)
47.      READ(105,12) (E(J), J=1,MM)
48.      12 FORMAT(8F9.3)
49.      READ(105,13) (E(J),J=MM+1,MMM)
50.      13 FORMAT(3F9.3)
51.      DO 200 N=MM+1,MMM
52.      OT(N) = T(E(N))
53.      200 CONTINUE
54.      DO 201 NN=1,MM
55.      IT(NN) = T(E(NN))
56.      SUM = 0.
57.      201 CONTINUE
58.      DO 103 II=1,MM
59.      SUM = SUM+IT(II)
60.      103 CONTINUE
61.      ITAVG = SUM/MM
62.      SUM = 0.
63.      DO 104 KK=MM+1,MMM
64.      SUM = SUM+OT(KK)
65.      104 CONTINUE
66.      OTAVG = SUM/(MMM-MM)
67.      WRITE(108,59)
68.      59 FORMAT('0','OUTER SPHERE TEMP.',10X,'DEVIATION',15X,'% DEVIATION',

```

```

69.      $//)
70.      DO 105 J=MM+1,MMM
71.      DEV(J) = OTAVG-OT(J)
72.      ERROR = DEV(J)/OTAVG*100.
73.      WRITE(108,55) OT(J), DEV(J), ERROR
74.      55  FORMAT(' ',4X,F10.4,11X,F10.4,16X,F10.4)
75.      105  CONTINUE
76.      WRITE(108,60)
77.      60  FORMAT('0','INNER BODY TEMP','//)
78.      DO 106 J=1,MM
79.      DEV(J) = ITAVG-IT(J)
80.      ERROR = DEV(J)/ITAVG*100.
81.      WRITE(108,55) IT(J),DEV(J),ERROR
82.      106  CONTINUE
83.      DT = ITAVG-OTAVG
84.      WRITE(108,56) ITAVG, OTAVG, DT
85.      56  FORMAT('1',//,'MEAN INNER BODY TEMP.      = ',F10.4,' R',//,'MEA
86.      $N OUTER SPHERE TEMP.      = ',F10.4,' R',//,'MEAN TEMP. DROP ACROS
87.      $$ GAP = ',F10.4,' R',//)
88.      IR = ID/2.
89.      OR = OD/2.
90.      RAVG = (OR+IR)/2.
91.      G = 32.174
92.      K = 0
93.      TM = (ITAVG+OTAVG)/2.
94.      WRITE(108,61) TM
95.      61  FORMAT('0',20X,'PROPERTIES BASED ON THE ARITHMETIC MEAN TEMPERATUR
96.      $E',////,'ARITHMETIC MEAN TEMP. = ',F10.4,' R')
97.      109  VIS = U(TM,I)
98.      SH = CP(TM,I)
99.      COND = CON(TM,I)
100.      DEN = RHO(TM,I)
101.      B = BETA(TM,I)
102.      PR = VIS*SH/COND

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103. C.... GRASHOF NUMBER BASED ON GAP THICKNESS
104. GR = G*B*DEN**2.*GAP**3.*DT*3600.**2./(1728.0*VIS**2.)
105. RA = PR*GR
106. WRITE(108,57) VIS, SH, COND, DEN, B
107. 57 FORMAT(' ',////,'VISCOSITY' = ',F10.4,' LBM/FT HR',//,'S
108. $SPECIFIC HEAT = ',F10.4,' BTU/LBM R',//,'THERMAL CONDUCTIV
109. $ITY = ',F10.4,' BTU/LBM FT R',//,'DENSITY = ',F10.
110. $4,' LBM/CU FT',//,'EXPANSION COEF. = ',F10.4,' 1/R')
111. WRITE(108,58) PR,GR,RA
112. 58 FORMAT(' ',////,'PRANDTL NO. = ',F15.4,//,'GRASHOF NO.
113. $ = ',F15.4,//,'RAYLEIGH NO. = ',F15.4)
114. K = K+1
115. IF(K.EQ.1) GO TO 110
116. GO TO 500
117. 110 TM = ((RAVG**3.-IR**3.)*ITAVG+(OR**3.-RAVG**3.)*OTAVG)/OR**3.-IR*
118. $*3.)
119. WRITE(108,62) TM
120. 62 FORMAT('1',20X,'PROPERTIES BASED ON THE VOLUMETRIC MEAN TEMPERATUR
121. $E',////,'VOLUMETRIC MEAN TEMP. = ',F10.4,' R')
122. GO TO 109
123. 500 CONTINUE
124. END

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1. C.... CONVERSION OF MILLIVOLTS TO DEGREES RANKINE SUBPROGRAM
2. FUNCTION T(E)
3. DIMENSION C(8)
4. DOUBLE PRECISION TOT
5. C(1)=491.96562
6. C(2)=46.381884
7. C(3)=-1.3918864
8. C(4)=0.15260798
9. C(5)=-0.020201612
10. C(6)=0.0016456956
11. C(7)=-6.6287090/(10.**5)
12. C(8)=1.0241343/(10.**6)

```

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13.      TOT=0.DO
14.      DO 1 I=1,8
15.      1  TOT=TOT+C(I)*(E**(I-1))
16.      T=TOT
17.      RETURN
18.      END

1.  C.... VISCOSITY SUBPROGRAM
2.      FUNCTION CP(T,I)
3.      GO TO (1,2,3,,)I
4.      1  CONTINUE
5.  C.... SPECIFIC HEAT OF AIR
6.      CO = 2.236775/(10.0**5)
7.      C1 = 0.22797749
8.      CP = C1+CO*T
9.      GO TO 50
10.     2  CONTINUE
11.  C.... SPECIFIC HEAT OF WATER
12.      C1 = 1.3757095
13.      C2 = .0012968965
14.      C3 = 1.1110533/(10.0**6)
15.      CP = C1-(C2-C3*T)*T
16.      GO TO 50
17.     3  CONTINUE
18.  C.... SPECIFIC HEAT OF 350 CS DOW 200 SILICONE
19.      TP = 5.0*(T-491.69)/9.
20.      C1 = 0.3259583
21.      C2 = 2.425/(10.0**4)
22.      C3 = 5.41667/(10.0**7)
23.      CP = C1 +(C2=C3*TP)*TP
24.      GO TO 50
25.     50 RETURN
26.      END

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1. C.... SPECIFIC HEAT SUBPROGRAM
2.     FUNCTION U(T,I)
3.     GO TO (1,2,3),I
4.       1 CO = 134.375
5.         C1 = 6.0133834
6.         C2 = 1.8432299
7.         C3 = 1.3347050
8.         U = T**C2/(EXP(C1)*(T+CO)**C3)
9.         GO TO 50
10.      2 TP = T-593.33203
11.        C1 = .0071695149
12.        C2 = .011751302
13.        C3 = .0087791942
14.        C4 = .81654704
15.        VIS = C1*TP+C2*(1.+C3*(TP**2))**.5+C4
16.        U = 1./VIS
17.        GO TO 50
18.      3 CONTINUE
19. C.... ABSOLUTE VISCOSITY OF 350 CS DOW 200 SILICONE
20.     V = .03875*(5.495*10**9)/(T-259.69)**2.943
21.     C1 = 52.754684
22.     C2 = .04537533
23.     C3 = 5.1832336/(10.**5)
24.     RHOW = C1+(C2-C3*T)*T
25.     RHO = RHOW*0.970
26.     U = RHO*V
27.     GO TO 50
28.   50 RETURN
29.     END

1. C.... THERMAL CONDUCTIVITY SUBPROGRAM
2.     FUNCTION CON(T,I)
3.     GO TO (1,2,3),I
4.       1 CONTINUE

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5. C.... THERMAL CONDUCTIVITY OF AIR
6.      XP = 0.1
7.      CO = -8.5964965
8.      C1 = 34490.89
9.      C2 = 868.23837
10.     C3 = 8056583.8
11.     10 X = XP
12.      F = CO+C1*X+C2*X*X+C3*X*X*X-T
13.      FP = C1+2.*C2*X+3.*X*X*C3
14.      XP = X-F/FP
15.      IF (ABS((XP-X)/X)-0.0001)20,20,10
16.     20 CON = XP
17.      GO TO 50
18.     2 CONTINUE
19. C.... THERMAL CONDUCTIVITY OF WATER
20.      C1 = .23705417
21.      C2 = .0017156797
22.      C3 = 1.1563770/(10.0**6)
23.      CON = -C1+(C2-C3*T)*T
24.      GO TO 50
25.     3 CONTINUE
26. C.... THERMAL CONDUCTIVITY OF 350 CS DOW 200 SILICONE
27.      CON = 0.00038/0.004134
28.      GO TO 50
29.     50 RETURN
30.      END

1. C.... DENSITY SUBPROGRAM
2.      FUNCTION RHO(T,I)
3.      GO TO (1,2,3),I
4.     1 CONTINUE
5. C.... DENSITY OF AIR AT LOCAL ATMOSPHERIC PRESSURE
6.      READ (105,100) BARO
7.     100 FORMAT(F10.4)

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```

8.      P = BARO*.491
9.      WRITE(108,101) P
10.     101  FORMAT(' ',//,'ATMOSPHERIC PRESSURE = ',F10.4,' PSI')
11.      RHO = BARO*.491*144./(53.34*T)
12.      GO TO 50
13.      2   CONTINUE
14.     C.... DENSITY OF WATER
15.          C1 = 52.754684
16.          C2 = .045437533
17.          C3 = 5.1832336/(10.**5)
18.          RHO = C1+(C2-C3*T)*T
19.          GO TO 50
20.      3   CONTINUE
21.     C.... DENSITY OF 350 CS DOW 200 SILICONE
22.          C1 = 52.754684
23.          C2 = 0.045437533
24.          C3 = 5.1832336/(10.0**5)
25.          RHO = C1+(C2-C3*T)*T
26.          RHO = RHO*.970
27.          GO TO 50
28.      50  RETURN
29.      END

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1.     C.... COEF. OF THERMAL EXPANSION SUBPROGRAM
2.      FUNCTION BETA(T,I)
3.      GO TO (1,2,3),I
4.      1   CONTINUE
5.     C.... EXPANSION COEF. OF AIR
6.          BETA = 1.0/T
7.          GO TO 50
8.      2   CONTINUE
9.     C.... EXPANSION COEF. OF WATER
10.      TP = T/100.
11.      IF(T-549.59) 10,10,20

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12.      10 C1 = 603.11841
13.      C2 = -353.03882
14.      C3 = 68.297012
15.      C4 = -4.3611460
16.      BP = C1+(C2+(C3+C4*TP)*TP)*TP
17.      GO TO 30
18.      20 C1 = -128.44920
19.      C2 = 68.827927
20.      C3 = -13.858489
21.      C4 = 1.2608585
22.      C5 = -.042495236
23.      BP = C1+(C2+(C3+(C4+C5*TP)*TP)*TP)*TP
24.      30 BETA = BP/(10.0**4)
25.      GO TO 50
26.      3 CONTINUE
27. C.... EXPANSION COEF. OF 350 CS DOW 200 SILICONE
28.      BETA = 0.00096/1.8
29.      GO TO 50
30.      50 RETURN
31.      END

```

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Cap. 2

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